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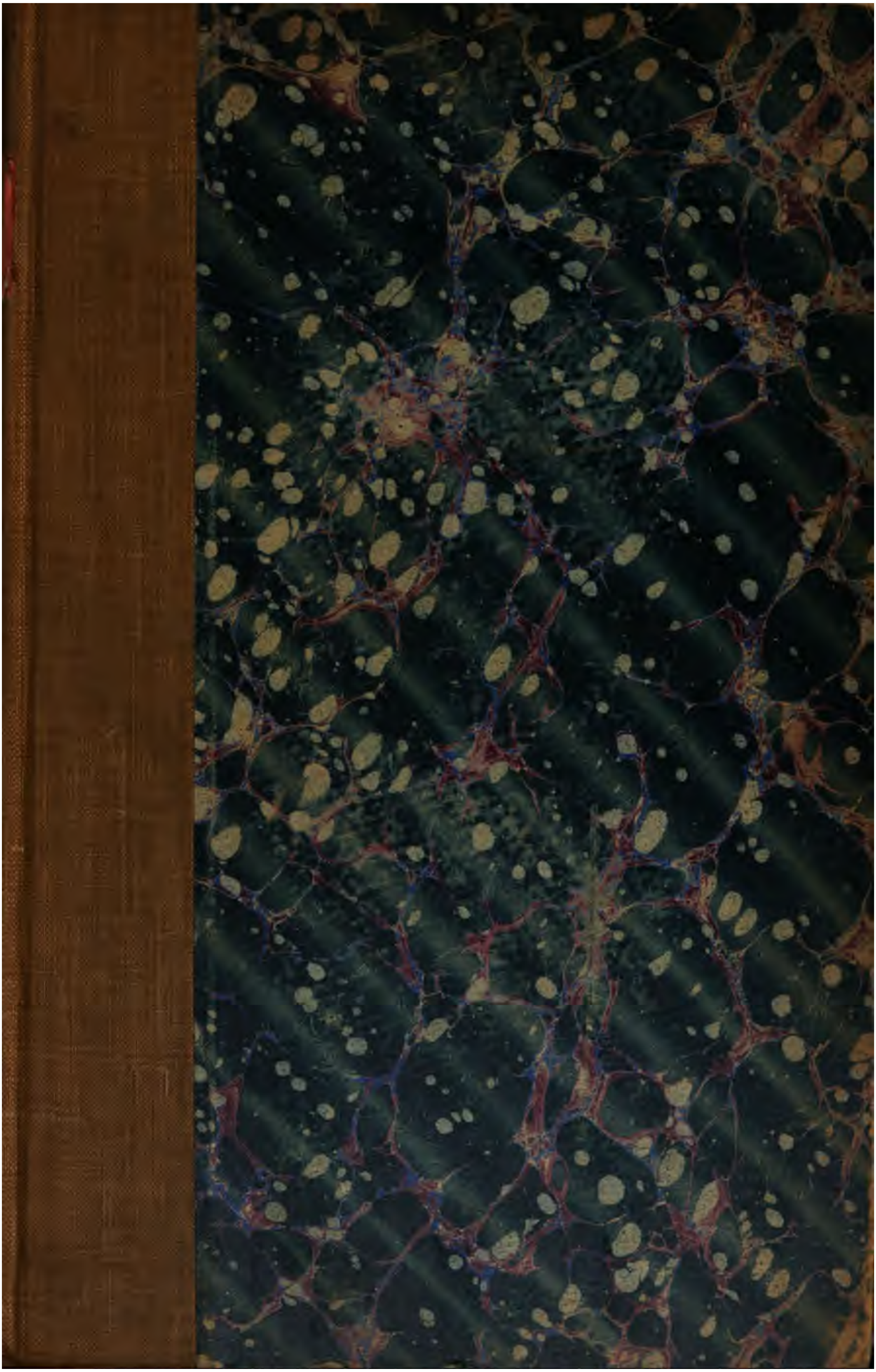

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AN INVESTIGATION OF ROTATIONS PRODUCED BY CURRENT FROM A SINGLE-PHASE ALTERNATOR

BY

ARTHUR CURTIS SCOTT

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AN INVESTIGATION OF ROTATIONS PRODUCED BY CURRENT FROM A SINGLE-PHASE ALTERNATOR.

PART ONE.

HISTORICAL SURVEY.

Christmas Day, 1821, marks the primary production of magnetic rotation, when Michael Faraday[1] (1791–1867), the greatest experimentalist of the nineteenth century in electricity and magnetism, obtained the revolution of a magnet around an electric current.

This first electro magnetic rotation was produced by placing a small magnet in mercury, one end being weighted with platinum to keep it in an upright position, and passing a current down through the mercury in a manner indicated by Fig. 1.

The apparatus of Faraday was soon modified by others of his contemporaries, among the first of whom was the noted Andre Marie Ampere[2] (1775–1836), who published an article in 1822 entitled "Action d'un aimant sur un conducteur circulaire."[3]

In 1823 came the invention by Peter Barlow[4] (1776–1826) of his rotating wheel (Fig. 2), which is the well known simple reverse of the disk dynamo invented by Faraday, eight years later, in 1831.

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[1] Faraday as a Discoverer, John Tyndall, N. Y. 1877, p. 12.
Historical Statement Respecting Electro Magnetic Rotation.
Exp. Researches, Vol. 2, pp. 159–162.

[2] See "Eulogy on Ampere," Arago, Smithson. Rep't, 1872.

[3] Ann. de Chimie et de physique (2), XXI, 47.

[4] On Magnetic Attraction (1823), 279.

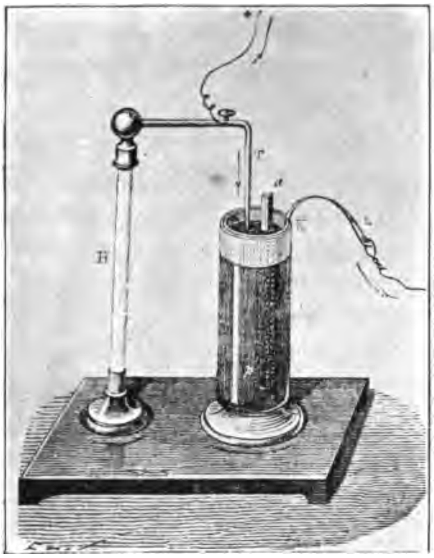

FIG. 1.

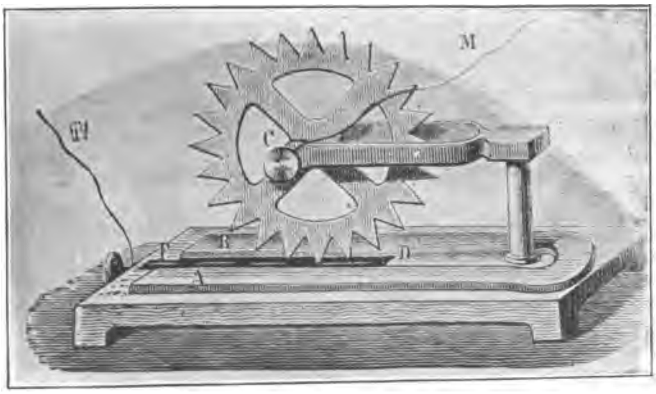

FIG. 2.

Supposing a uniform field of intensity H perpendicular to the plane of the disk of surface S, and a wheel of radius r, the flux of force for a rotation of an angle α varies from

$$\frac{H\ r^2 \sin \alpha}{2} \text{ to } \frac{H\ r^2 \alpha}{2}$$

and the corresponding work is equal to

$$\frac{H\ I\ r^2 \alpha.}{2}$$

For one turn, this work has a value

$$\frac{H\ I\ 2\ \pi\ r^2}{2} = H\ I\ S$$

If the disk makes (n) turns in (t) seconds, then the mechanical power which can be produced is

$$P = \frac{n}{t} H\ I\ \pi\ r^2 = E\ I;$$

whence may be deduced the electromotive force

$$E = \frac{n}{t} \pi\ H\ r^2 = \frac{\omega\ H\ r^2}{2}$$

where ω equals the angular velocity in radians per second. This gives a type of electric motor which is theoretically perfect.

The next important contributions which were made to this subject came by several men almost simultaneously, so that actual priority by either is indeterminate. It appears, however, that Gambey, a Paris instrument maker, happened to notice that a compass needle was visibly damped in its oscillations by the presence of a thick plate of copper. This observation is thus described by Verdet[5] "En 1824, on observa dans l'atelier de Gambey, que les oscillations de l'aiguille de declinaison s'amortissent plus vite en présence d'une plaque épaisse de cuivre rouge que dans l'air.

Cette observation donna lieu à un perfectionnement important dans la construction des galvanomètres. On disposa sous l'aiguille un disque èpais de cuivre rouge, qui agit sur l'aiguille lorsqu'elle oscille et diminue le temps nécessaire pour qu'elle atteigne sa position d'équilibre. Arago, à qui l'on communiqua ce fait, y reconnut la preuve de l'action d'une force qui n'existe qu'autant que l'aiguille on la masse de cuivre est en mouvement, et donna á l'expérience une forme remarquable."

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[5] Conférences de Physique, 1872, 1. 415.

Dominique François Jean Arago[6] (1786–1853) having thus learned of the phenomenon, if not the first to discover it (in 1822), as claimed by some, was unquestionably the first to publish an account of it at the Académie des Sciences, November 22nd, 1824. Arago suspended a compass needle within rings of different materials and noted the difference in the number of oscillations made by the needle before reaching a point close to that of equilibrium, and found the number in wood to be about 145, in thin copper 66, and in thick copper 33. He supposed that the force only existed during the time

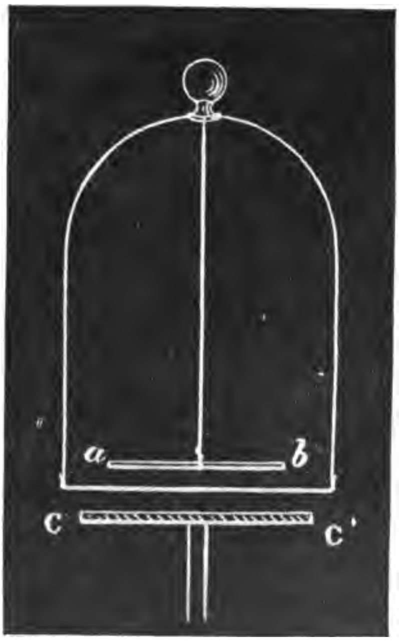

FIG. 3.

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[6] OEuvres complétes, IV, 424.

of the relative motion between the needle and the copper, and so spoke of the phenomenon as the "magnetism of rotation."

Later (in 1825) he published a further experiment[7] in which he produced a reactionary effect upon a magnetic needle by the rotation of a copper disk beneath it. The apparatus constructed by Arago for verifying his ideas of action and reaction in this matter is indicated by Figures 3, 4, and 5. A disk of copper (CC^1) (Fig. 3) receives by means of a clock mechanism a very rapid rotation. A magnet needle (ab) is suspended by a torsionless fibre above this disk. A sheet of paper separates the needle from the air enveloping the disk, and the needle is covered by a bell jar. When the disk is motionless, the needle takes a position of equilibrium which is at once abandoned as soon as the disk begins to move, the deviation taking place in the direction of rotation and increasing with the rapidity of movement, until the deflection exceeds 90 degrees when the needle then turns with great rapidity. Thus when a metallic disk is in motion beneath a magnetic needle there exists a force which tends to drag the needle. Is it necessary then to conclude that this force is directed tangentially to the circle described by the needle? No, because a component of the force which would be perpendicular to the plane of the disk would be without effect on the movement of the needle; it would be the same as a component directed along the radius; the movement of the needle indicates only that it has a component directed along a tangent to the circle described.

"Arago also determined two other components of the force on the needle. To do this he made experiments in which the needle was at liberty to move in two directions perpendicular to the preceding." * * * "In order to ascertain whether the force has a component perpendicular to the plane of the disk, the needle (ab) (Fig. 4) is suspended vertically from beneath one of the pans of a balance, and the disk (CC^1) is set in rotation. It is found that the weight of the needle appears to decrease. Consequently the needle is urged, in the first experiment (Fig. 3) by equal forces applied to the two poles, which tend to raise or repel the needle.

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[7] Annales de chimie et de physique 2, t, XXVII, 363, 1824, et t, XXVIII, 325, 1825.

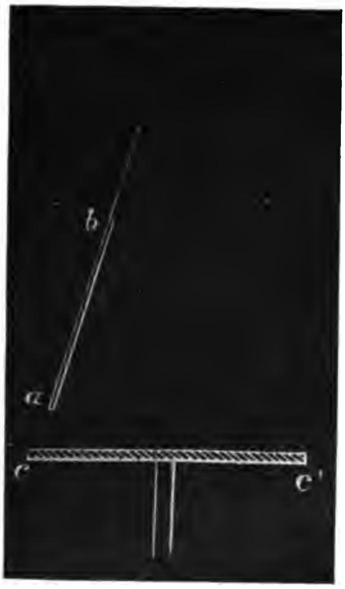

FIG. 4.

"For investigating whether the force has a component parallel to the radius a needle is used which cannot turn about a horizontal axis. A dip needle is so placed that the plane of rotation is perpendicular to the magnetic meridian; it is then vertical. The centre of the disk is now placed in the vertical plane in which the needle may turn, and successive projections of the needle are made. It is proved thus that when the projection P (Fig. 5) from the centre of the needle upon the plane of the disk, falls outside of the disk M. N. the lower pole A is repelled. When the projection approaches the edge M. this force increases, and is sensibly a maximum when P is a little inside of the edge. Then the force diminishes becoming zero when the lower pole approaches the centre to a certain limit; here the needle is again deflected inward as shown by the figure, and finally 'becomes vertical on the axis.'

"The latter experiment arranged for the diameter of the disk perpendicular to the plane of the magnetic meridian is evidently valid for all the others, because this arrangement does not eliminate the earth's influence. Knowing thus the component of the action of the disk on the magnet, the intensity of this action may be deduced."[8]

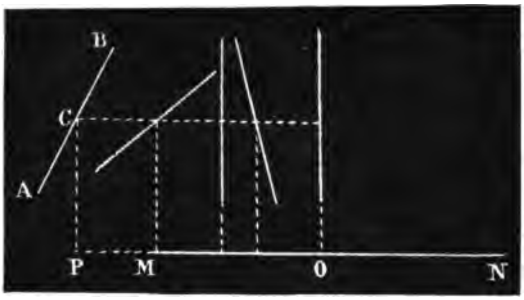

FIG. 5.

As these experiments were receiving widespread attention the French mathematician Siméon Denis Poisson (1781–1840) thoroughly imbued with the theories of Coulomb concerning magnetic action at a distance, sought to explain the facts on a theory of magnetism of rotation,[9] which presumed that all substances acquire a temporary magnetism in the presence of a magnet, and that in copper the temporary magnetism remained a longer time than in other metals. The theory did not account for the facts, however, as pointed out by Arago, yet on the authority of Poisson, it was generally adopted at the time; it seems quite possible that had it been considered of less importance, the phenomenon of induction might have been discovered at an earlier date.

There is, however, a somewhat remarkable point in Poisson's theory in that it enunciated for the first time the presence of the time element in the modification of the magnetic state of a body.

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[8] Translation—Conférence de physique. IV, 1, 1872, pp. 416–418.

[9] Memoires de l'Academie des Sciences, t, VI, p. 439.
Annales de chimie et de physique [2], t, XXXII, p. 225, 306.

On May 5, 1825, a letter from Peter Barlow[10] to Herschel was read before the Royal Society, "On the temporary magnetic effect induced in iron bodies by rotation," in which he describes his experiments and observations on the effect produced on a magnetic needle when a sphere of iron is rotated near it.

Another exhaustive paper dealing with experimental and theoretical investigations was presented to the same Society on May 12th of the same year by Samuel Hunter Christie,[11] (1784–1865) entitled "On the Magnetism of Iron arising from its rotation," and on June 16th, Charles Babbage (1792–1871) and J. H. W. Herschel[12] (1792–1871) gave an "Account of the repetition of M. Arago's experiments on magnetism manifested by various substances during the act of rotation." It was they who measured the retarding force of different materials acting upon the needle and found them to stand in the following order, Copper, Zinc, Tin, Lead, Antimony, Bismuth, Wood, from that of the most powerful to that of the least so. They also showed that radial slits in the copper disk over a revolving magnet, diminished the tendency of the disk to rotate. The appearances of the disks, the times of rotation, and the forces observed for the various experiments are shown in Fig. 6.

In 1826 Ampere[13] found that a rotating disk of copper caused the turning effect upon a neighboring wire carrying a current.

Other experiments along this line were carried out about this time by scientific men in Germany, Switzerland, and Italy, though little of great importance was added to the knowledge of the subject until the publication of Faraday's brilliant research on magneto-electric induction, in 1831. Faraday[14] showed that the relative motion between magnet and metal disk produced currents in the disk, which by a reactionary effect tended always to diminish this relative motion. He further demonstrated that these currents go eddying around in the moving disk, and may be led away by sliding contacts.

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[10] Royal Society Transactions, 1825, p. 317.

[11] Royal Society Transactions, 1825, p. 347.

[12] Royal Society Transactions, 1825, p. 467.

[13] Action d'un disque en mouvement sur un conducteur voltaique," Ann. de chimie et de physique (2) t, XXXII, 322.

[14] Experimental Researches.

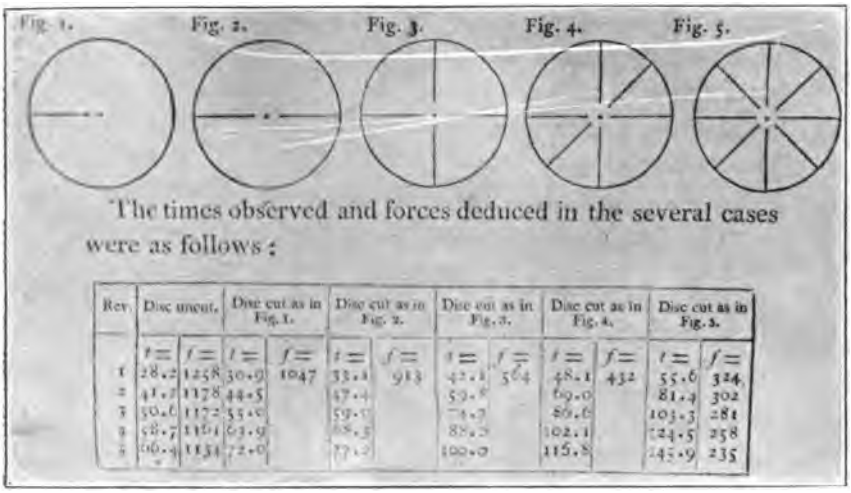
Fig. 1.
Fig. 2.
Fig. 3.
Fig. 4.
Fig. 5.

The times observed and forces deduced in the several cases were as follows:

Rev.	Disc uncut.		Disc cut as in Fig. 1.		Disc cut as in Fig. 2.		Disc cut as in Fig. 3.		Disc cut as in Fig. 4.		Disc cut as in Fig. 5.	
	$t=$	$f=$	$t=$	$f=$	$t=$	$f=$	$t=$	$f=$	$t=$	$f=$	$t=$	$f=$
1	28.2	1258	30.9	1047	33.1	913	42.1	564	48.1	432	55.6	324
2	41.2	1178	44.5		47.4		59.8		69.0		81.4	302
3	50.6	1172	55.0		59.0		73.7		86.6		103.3	281
4	58.7	1161	63.9		68.5		88.3		102.1		124.5	258
5	66.4	1151	72.0		77.2		100.0		115.8		145.9	235

FIG. 6.

William Sturgeon[15] (1783–1850) made experiments to determine the eddy current paths in the disk, and Charles Grafton Page[16] (1812–1868) investigated with special apparatus the time element in connection with induction. In 1853 Carlo Matteucci[17] (1811–1868) made extended investigations concerning the distribution of eddy currents in the turning disk of Arago, which in turn were highly modified at a later date by Emil Carl Gustav Georg. Jochmann[18] (1833–1871), who also investigated mathematically the induction in a rotating sphere, and later by Heinrich Hertz[19] (1857–1894).

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[15] Edin. Phil. Jour., 1825, July.
Phil. Mag., 1832, April and May.

[16] Verdet, Conférences de physique IV, I, 428.
Annales de chimie et de physique (3) XXXI, 187, 1850.

[17] Sur la distribution des courants electriques dans le disque tournant d'Arago. Ann de chimie et de physique (3) XXXIX 129, 1853. Ann. de chimie et de physique (3) XLIX 129, 1857.

[18] "Ueber die durch Magnet pole in rotirenden körperlichen Leitern inducirten elektrischen Ströme."
Poggendorff's Annalen, CXXII, p. 214, 1864.

An interesting experiment said to have been originated by Julius Plücker[20] (1801–1868) is arranged in accordance with Fig. 7. Between the poles A and B of a powerful electro magnet is suspended a cube of copper C. A movement of rotation is given the copper cube by means of its suspension and when it is in most rapid motion the current is turned upon the electromagnet, resulting immediately in the retardation or stopping of the rotation of the cube. This experiment has also been made still more important by Matteucci, who used a laminated cube instead of a solid one. If the planes of the laminae are parallel to the direction of the lines of force no effect is produced by the magnet upon the rotating cube, but if it be hung so that the planes of the laminae are perpendicular to the direction of the lines, then the effect is very pronounced, for in the latter case only can eddy currents circulate, since their paths must be in planes at right angles to the magnetic lines.

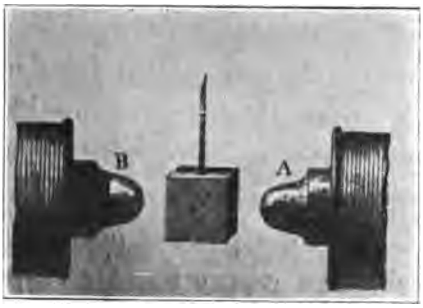

FIG. 7.

Jean Bernard Léon Foucault[21] (1819–1868) devised an apparatus in 1855 (Fig. 8) for proving the existence of eddy currents in a striking manner. A disk of copper D placed between the poles (A. B.) of a powerful magnet was arranged so as to be given a very rapid rotation. When the magnet was excited the energy required to turn the disk became noticeably greater, and if a uniform rate of rotation was maintained the energy thus absorbed soon raised the temperature of the disk. As Foucault was the first to show this heating effect, such currents have been called Foucault currents; it should be remembered, however, that he merely reviewed and extended in one particular the original discovery of Arago of some years previous, and also that Faraday had completely demonstrated the fact that Arago's rotations were due to induced eddy currents.

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[19] Phil. Mag., 1880, Wiederman's Beiblätter, 1880, 8, pp. 622–624.

[20] Conférences de Physique, Verdet IV, I, 430.

[21] Annales de chimie et de physique, (3) XLV, 316, 1855.

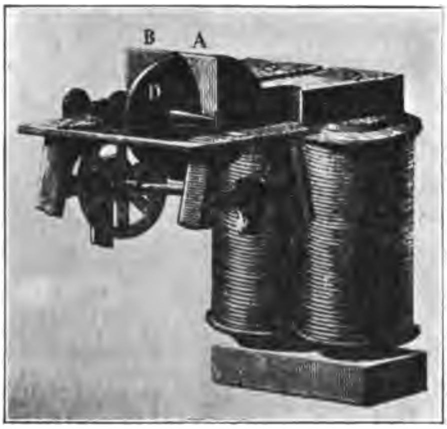

FIG. 8.

It remains as a singular fact that despite the early knowledge concerning the Arago rotations no one appeared to consider them valuable in the construction of a motor until the year 1879. It is true that electric motors had been constructed at an earlier date, the same depending upon the principle of attraction by the electro magnet, but they were concerned with continuous currents and so do not apply particularly to the subject here considered. In order to cover the field, however, the names of some of the early inventors of motors deserve mention in passing, and so we find in order the Abbé Salvatore del Negro[22] (1768–

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[22] Annali delle Scienze–Lombardo–Veneto.

1839), in 1830; Joseph Henry[23] (1799–1878), in 1831; William Ritchie[24] (——–1837), in 1833; Moritz Hermann Jacobi[25] (1801–1874), in 1834. The motor of Jacobi was used by its inventor in 1838 to propel a boat carrying fourteen passengers on the River Neva, the motor current being furnished by 320 Daniell cells, and in point of design was somewhat similar to some of the modern alternating current generators.

Robert Davidson[26] (—— ——), in 1837, is said to have placed an "electro-magnetic" locomotive on the Edinburgh and Glasgow railway which ran at a speed of four miles per hour; his conception of the electric railway, however, seems to be antedated by that of Davenport[27] (—— ——) a blacksmith, of Brandon, Vt., who constructed a motor based on the principle of Jacobi's motor, and put it in operation on a small circular railway at Springfield, Mass., in 1835.

The discovery of the reversibility of the action of generator and motor appears to be due to Heinrich Friedrich Emil Lenz[28] (1804–1865), though accredited by some authors to M. H. Jacobi. Other noted inventors along this line in later years were Sir Charles Wheatstone[29] (1802–1875) of England, in 1841; C. G. Page[30] of the United States, in 1850; Paul–Gustav Froment[31] (1815–1865) of France, in 1857; and Antonio Pacinnotti[32] (1841–——) of Italy, in 1865, while the principle of power transmission from one machine as generator to another as motor was first practically demonstrated by Hippolyte Fontaine (1832– ——) and Zénobe Theophile Gramme (—— ——) at an exhibition in Vienna, in 1873.

In 1879 Walter Baily[33] (1837– ——) showed that rotation of a copper disk could be produced by currents induced therein, when placed in a systematically changing magnetic field, and exhibited to the Royal Society the first induction motor. This motor (Fig. 9) really amounted to an apparatus for producing Arago's rotations, not by means of a revolving magnet which acted upon the copper disk to cause its rotation, which had been the only method employed down to that time, but by means of two fixed horseshoe magnets, the alternating magnetism in which was made to shift progressively between the four successive poles. Eddy currents were produced in the copper disk above the poles, which by their reaction caused the disk to move in the direction of the progression of the poles. Evidently it was not considered at the time that the application of Arago's rota-

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[23] Silliman's Journal, XX, 340, 1831.
[24] Phil. Transactions, (2), 318, 1833.
[25] L'Intitute, LXXXII, Dec., 1834; Prac. Elec. Eng., Vol. II.
[26] Practical Electrical Engineering, Vol. II.
[27] Practical Electrical Engineering, Vol. II.
[28] Pogg. Ann., XXXI, 483, 1838; Annals of Elec., III, 384, 1838.
[29] Spec. of British Patent, 9022, 1841.
[30] Silliman's Journal, LX, 341, 1850.
[31] La Lumiere Electrique, IX, 19.
[32] Nuovo Cimento, XIX, 378, 1865.
[33] Phil. Mag., Vol. VIII, No. 49, p. 286, Pl. IX and X, 1879.

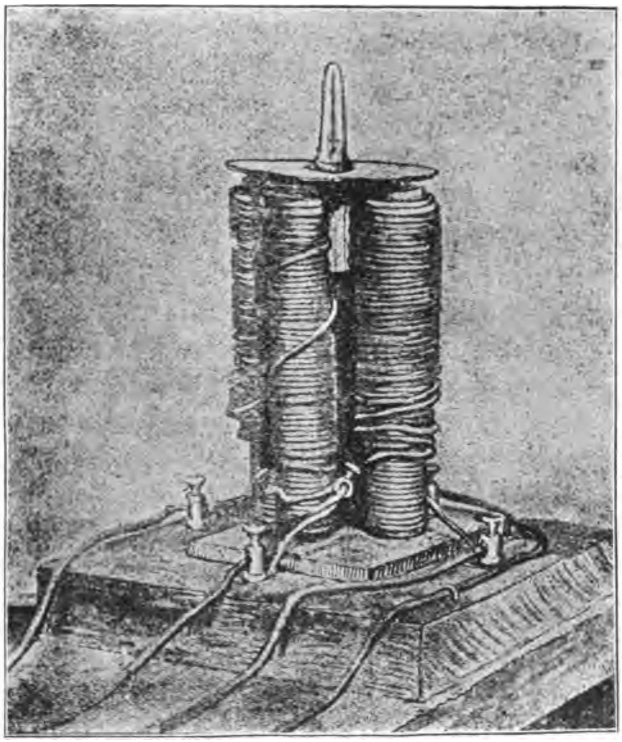

FIG. 9.

tions in such a manner was of practical importance, though further experimental work continued to slowly proceed.

The same year 1879 Frederick Guthrie (1830–1886) and C. Vernon Boys[84] (—— ——) investigated quite completely the action of a rotating magnet upon a copper plate supported above it. They pointed out some interesting facts, including the relation of torsion to velocity, the variation of torque with conductivity for various metals, and the application of their method to the determination of the conductivity of liquids.

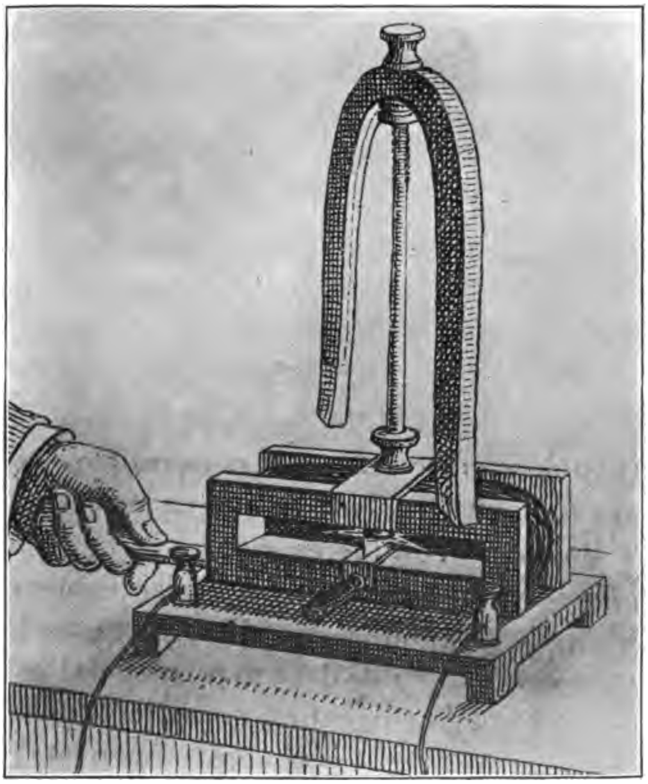

FIG. 10.

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[84] "On Magneto Electric Induction." Phil. Mag., Vol. VIII, No. 51, 449, Pl. XIII.

The following year in 1880 Wilfred de Fonvielle (1828–——), and D. Lontin[35] presented a novelty to the Paris Academy in their so called *"gyroscope magnetique."* A representation of their apparatus is shown in Figure 10, and its object was to show new properties of induction currents in a magnetic field, by giving a rotatory motion to movable pieces of very soft iron of various forms.

The apparatus consisted of a galvanometer frame wound with a coil of wire as shown. Inside the coil was placed a disk or modification of a disk, of soft iron, which was lightly pivoted and free to rotate, above which a horseshoe magnet was so mounted as to be placed in any azimuthal position. It was also possible to place bar magnets underneath the frame or in various positions about it. When current from a Ruhmkorff coil was sent through the circuit a variety of rotatory effects were produced when the magnets were placed successively in different positions; rotations were also obtained without the use of magnets, if the disk were given an initial velocity. The inventors were led to conclude that the rotatory effect was exercised on each molecule of iron and that the total movement was the integral of the individual impulsive effects.

Jules Célestin Jamin[36] (1818–1886) offers a criticism of this explanation, which is in turn answered by De Fouvielle.[37] A further consideration of this apparatus by Jamin is as follows:[38]

"I assume that we have done away with the magnet and that we cause to pass into the galvanometer frame the alternating discharges of a Ruhmkorff coil. The first will magnetise the disk transversely, and, when it shall have ceased, it will preserve a portion of its magnetism. When the second discharge, which of opposite direction, occurs it should produce two successive effects; first, act upon the residual magnetism and tend to displace the disk; second, destroy the first magnetization and replace it by another which is opposite. Let us consider the first effect. At the moment when the second discharge begins, it tends to deflect the disk 180 degrees; it is then in unstable equilibrium. If it is unmovable, it will not be displaced; but if it has received in the first instance, in one direction or in the other, a speed which has deflected it by an angle (a) it should receive an impulse which will maintain and continue its movement. This impulse will be renewed at each change in the direction of the discharges; we can represent it by F sin (a) and by F_1 sin (a) for direct and inverse currents, and the total resulting couple by $(F+F_1)$ sin (a). The action of terrestrial magnetism comes in to complicate the action. Let us first assume the frame perpendicular to the plane of the meridian; the magnetization will be in this plane; and the disk will be in stable equilibrium for the direct discharges, unstable for the inverse, and the contrary will be true if we change the direction of the inductive current. The terrestrial action will be then reduced to a couple $\pm (\phi - \phi')$ sin (a), and the total effect will be expressed by $(F + F_1)$ sin (a) $\pm (\phi - \phi')$ sin (a).

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[35] Mouvements giratoires continus produits par une machine d'induction rotative. Compte Rendus. t. XC, 800, 1880.

[36] Sur l'explication de l'experience de M. M. Lontin et de .Fouvielle. Comp. Rend. t, XC, 839.

[37] Compte Rendus t. XC, 1880.

[38] Translation from Compte Rendus, t. XCI, 1880.

Summing up this: first, the disk will take on no movement if it is primarily immovable; second, it will continue to revolve in one direction or the other if there has been primarily a velocity imparted to it; third, these two velocities will be unequal; their sum will be a measure of $(F+F_1)$, and their difference $(\phi - \phi')$. The condition will change if the frame is in the magnetic meridian; in this case, the magnetization will be perpendicular to this plane, the terrestrial couple will be $\pm (\phi - \phi')$ cos (a), and the total moment can be represented by $(F+F_1)$ sin (a) $\pm$ $(\phi - \phi')$ cos (a). First, the terrestrial action will be predominant; second, it will impart to the immovable disk a movement whose direction will change with the inducing current; third, the two velocities will be unequal; their difference or their sum determines $(\phi - \phi')$ cos (a) and $(F+F_1)$ sin (a). Finally: if the frame makes an angle of $90-\delta$ with the magnetic meridian, the couple becomes $(F+F_1)$ sin (a) $\pm (\phi - \phi')$ cos $(\delta + a)$ and there will be one value for which one of the velocities is nil. The values of F and F_1 are proportional to the mean square of the mean strength of the discharges, those of ϕ and ϕ' to the first power of these strengths. Experiment will show how $F+F_1$ and $\phi-\phi'$ vary when these strengths change. We can reduce the phenomena to the single action of the direct discharges by interposing an air resistance in order to annul the inverse discharges. If it is thought that almost nothing is known as to the duration and strength of the alternating and rapid magnetization produced by induction currents, it will be recognized that the experiment of Mr. Lontin is not alone curious, but that it can become in the hands of experimenters a source of valuable information as to a very obscure subject. I hope that Messrs. Lontin and DeFouvielle will be disposed to carry out this investigation and that they will pardon me for having pointed out to them all the advantage that they could derive from their experiments."[39]

In 1880, Marcel Deprez[40] (1843- ——) tested some two phase motors, one of them of one eighth horse power having a fixed field produced by permanent magnets. Between the poles of these magnets revolved an armature with two coils which were traversed by currents 90 degrees apart though it was really nothing more than the combination of two motors placed at right angles in such a way as to have no dead points, as indicated by Figure 11. In 1883 Deprez[41] further communicated to the *Academie des Sciences* an important theorem on the rotary magnetic field, by combining two alternating fields having difference of phase of a quarter period.

In 1887, Elihu Thomson exhibited some apparatus which illustrated what he termed "Novel Phenomena of Alternating Currents," some of the underlying principles of which apparently explain the action of the peculiar apparatus of De Fonvielle and Lontin, and which have been used more or less extensively in single phase small motor design. A variety of forms of apparatus for showing the "Novel Phenomena" were devised by Mr. Thomson,[42] but only those of fundamental importance can be here considered. Figure 12 represents a tethered copper or aluminum ring, which is supported in the air like Mahomet's fabled coffin, against the force of gravity because of a simple alternating current flowing through the coils of an electromagnet. A copper or aluminum disk, if light enough is repelled by the force, in the same way as the ring.

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[39] A theory of the action of De Fonvielle's apparatus was presented in a memoire to the Academie des Sciences, by A. Picard, which is simply referred to in the Compte Rendus, XC, 1880. This paper could not be located for consultation.

[40] Courants Alternatifs Industriels, Loppe et Bouquet, Vol. II, 1896.

[41] Compte Rendus, 1883, 1193.

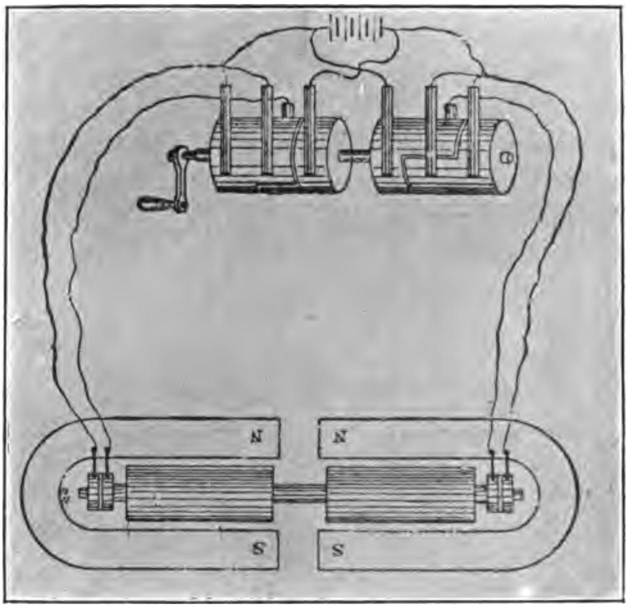

FIG. 11.

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[42] For more complete description of apparatus and numerous cuts illustrating the same, the reader is referred to the following papers:

Trans. American Institute of Elec. Engineers, 1887.
Elec. World, IV, May 28, 1887.
Elec. World, XIV, Dec. 5, 1889.
London Electrician, May 16, 1890.
London Electrician, May 23, 1890.
London Electrician, May 30, 1890.

The last three papers embrace a very complete elementary treatment by Dr. J. A. Fleming. For an analytical treatment of the subject see Proc. Royal Institution, XIII, 1891, p. 296, J. A. Fleming, and Phil. Trans. Royal Society, 1892, p. 279, G. T. Walker.

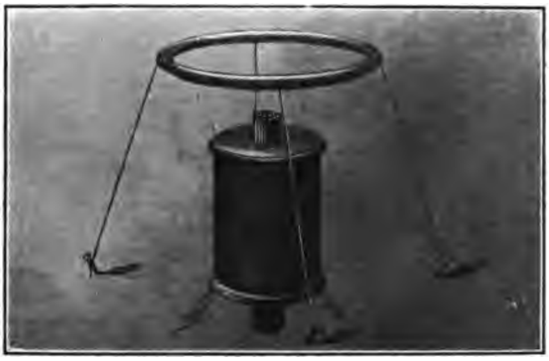

FIG. 12.

In order to completely explain this effect it is perhaps best to begin with extremely elementary considerations. A simple harmonic, or sine function of time can be represented by an alternating vector, which at the same time represents the wave form of an alternating current, and is shown to vary as time goes on by the curve O. A. B. C. D. (Fig. 13).

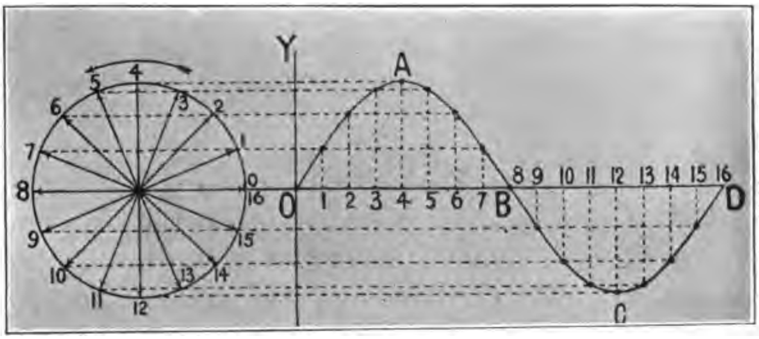

FIG. 13.

Now if the ring or disk has a zero time constant, that is, if the currents induced therein by the alternating magnetism in the coil increase and decrease in strength in exact synchronism with the inducing force creating them, it is easy to show that these currents are at a maximum intensity when the reversal of magnetism occurs in the magnet. Considering Fig. 14, let O. B. represent a rotating vector of length A, and angular velocity ω. Its projection on the y axis O. B_2 at any instant gives an alternating vector, whose rate of change at the instant is shown by the velocity of the extremity B_2. The velocity BC of B is equal to the angular velocity times the radius, or ωA. If a line OS is drawn parallel and equal to BC, this line represents the velocity of B at the given instant, and hence the velocity of B_2 is the projection of OS on the y axis. Then OS_2 is the rate of change of the alternating vector when the latter has a value OB_2 and is increasing. Now if the speed ωA of the point B is constant, O S will remain of constant length ω A. Again since O S is always at right angles to O B, O S revolves about O with constant angular velocity ω, therefore O S will

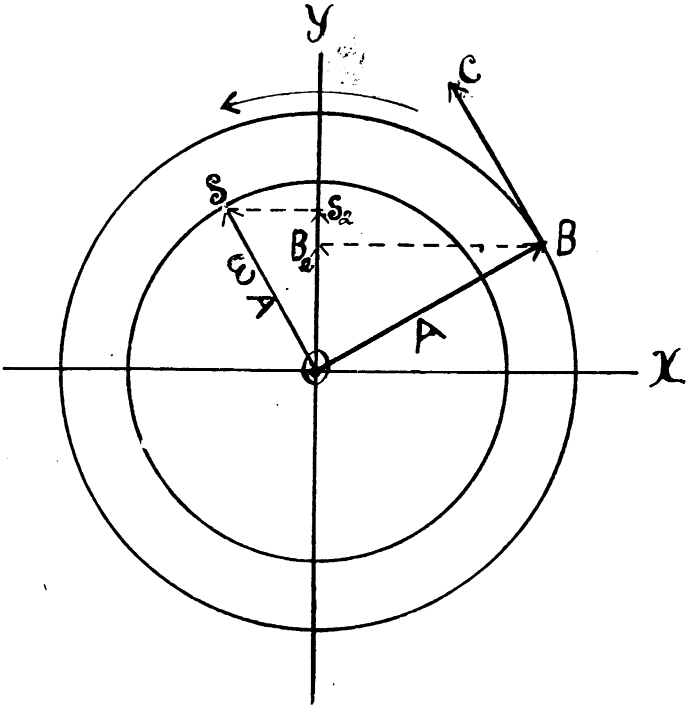

FIG. 14.

be a rotating vector and its projection $O S_2$ will be an alternating vector. The rate of change of the alternating vector of amplitude A and period $\frac{2\pi}{\omega}$ can thus be represented by another alternating vector of the same period, of amplitude ωa, and $\frac{\pi}{2}$ degrees away from the first in position; or if the vector be denoted mathematically by $A \sin \omega t$, its rate of change is denoted by $\omega A \sin (\omega t \pm \frac{\pi}{2})$. If therefore the ring or disk have zero time constant, or be non-inductive, the currents therein would be in phase with their E. M. F.'s, and the resultant force at any instant being proportional to the product of current and field intensity at that instant would be zero since the mean value of the product of two sine functions in quadrature is zero. The result is indicated by Figure 15, which shows that the attractive impulses balance the repulsive and so the disk or ring would not move. Every conductor must, however, have a measurable time constant, and so when the ring or disk possesses such an amount of self-induc-

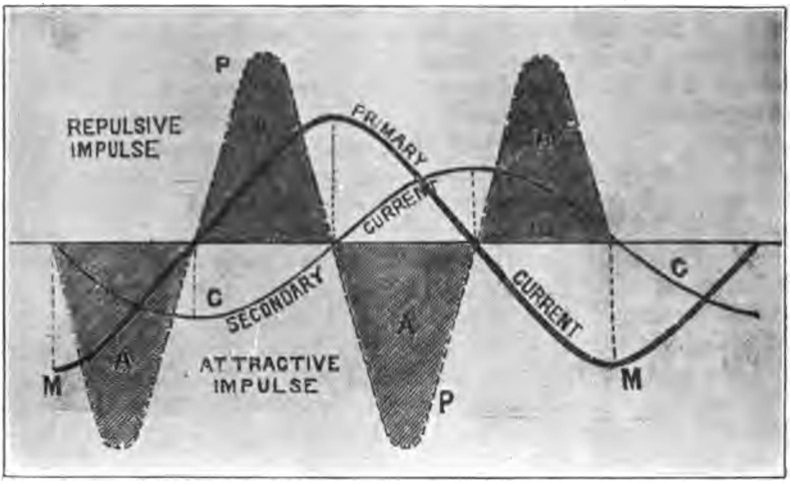

FIG. 15.

tion that the current induced lags behind the inducing electromotive force in phase, the resulting force is not zero but is a positive one of repulsion.

Figure 16 shows clearly the effect produced when the instant of maximum current in the ring occurs later than the instant of the reversal of magnetism. The shaded areas which lie above the zero line and which represent the repulsive influences are much larger than the corresponding shaded portions below the line which indicate attractive impulses. A glance at the Figures in consideration of foregoing remarks is sufficient to clear up this peculiar phenomenon.

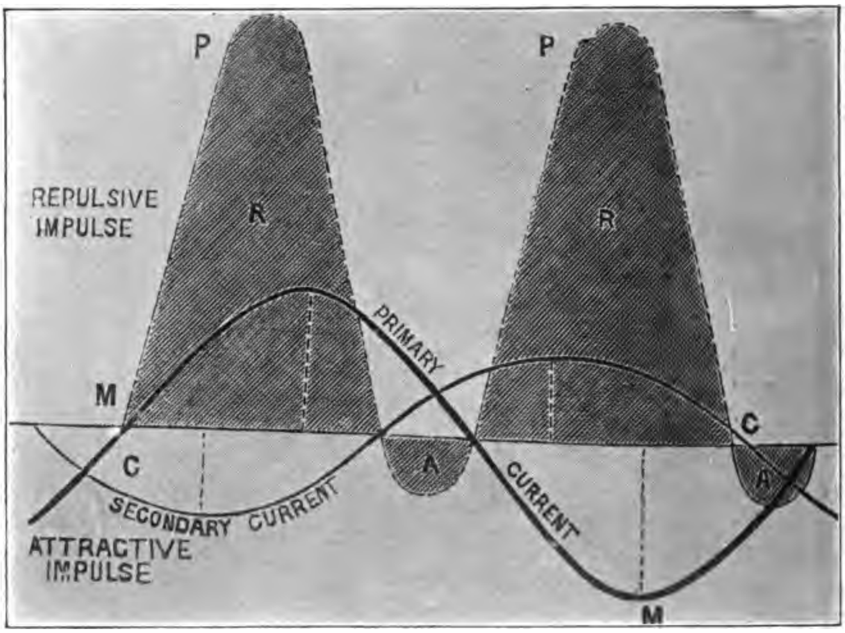

FIG. 16.

It is easy to understand that open circuit coils, or disks having radial slits would not exhibit this repulsive effect, since in that case no currents are induced, because there are no paths in which they can move. It is found that where repulsive effects alone are considered, aluminum is the best metal to use, since that metal has the highest conductivity per unit of mass; though the greatest force is produced in copper or silver, because these metals have the greatest conductivity per unit of volume.

Figure 17 shows another interesting application of this principle in the production of current in a coil immersed in water, of sufficient intensity to light the lamp attached, and at the same time the repulsive force maintains the coil in equilibrium above

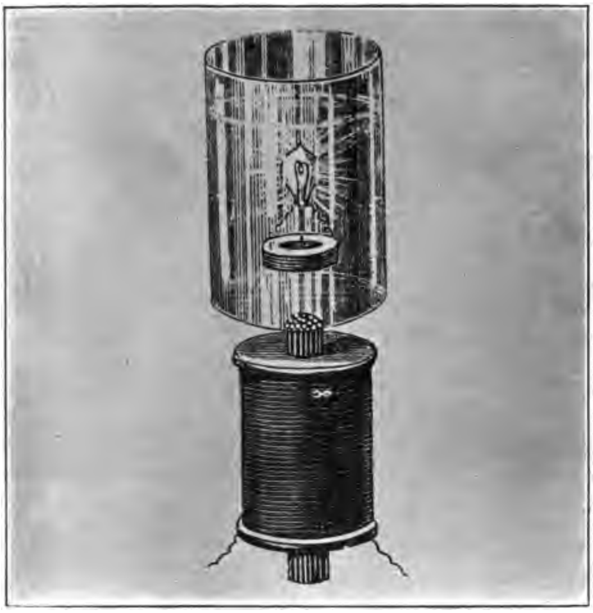

FIG. 17.

the magnet. If now a copper plate be introduced between the magnet and the coil the lamp no longer remains lighted, because the copper acts as a screen and the current which would light the lamp now circulates in the copper plate.

The experimental data on such phenomena led Thomson to the statement of four laws concerning it.[43] 1. "If two or more closed circuits are similarly effected inductively by an alternating magnetic field they will attract one another, and tend to move into parallelism. 2. Iron or steel masses placed in an alternating field give rise to shifting magnetism or lines of force moving laterally; and may, therefore, act to move closed circuits in the path of such shifting lines. 3. Closed circuits in alternating magnetic fields or fields of varying intensity give rise to shifting magnetism, or lines of force moving laterally to their own direction; and may, therefore, act to move other closed circuits in the path of such lines. 4. Iron or steel masses may, when placed in an alternating magnetic field, interact with other such masses, or with closed electric circuits, so as to produce movement of such masses or circuits relatively, or give rise to tendencies to so move, the effects depending upon continual adaptations of shifting magnetism and retained magnetism relatively." Many very ingenious applications of the above facts have been made by Thomson, fairly complete representations of whose apparatus will be found in the articles already cited. Photographs of like apparatus as used by the writer, in experimental work together with those illustrating some further extension of the application of the principle involved will be found in Part II of this paper.

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[43] Elektrotechnische Zeitschrift, July 18, 1890, Vol. 12, p. 400.

Before passing to the important contributions made to the subject by Ferraris and Tesla whose works were not published until 1888, a few patents filed at an earlier date deserve mention. The two first of these to be considered were issued to Elihu Thomson,[44] in 1887, and of the first he says in part:

"My present invention depends upon the discovery made by me that through the induction exercised by an alternating current or magnetic field upon a closed circuit of low resistance and high self-induction forming another coil or closed band and through the self-induction of the electric currents set up in the latter, a repulsive action is established, resulting in a tendency of the closed circuit coil or conductor to move away from its inducing field. My present invention consists in a suitable combination of the devices referred to with a commutator, as will be hereinafter described whereby, through an alternating current, continuous movement, oscillatory or rotary, may be produced in a similar way to that which is produced in ordinary electric motors by the operation of a continuous electric current. Figures 1, 2, 3, 4, 5, 6, and 7 (Fig. 18), illustrate devices embodying the principle which I utilize in carrying out my present invention. Figure 9 is an end view of the same. Figure 10 is a side view and section of a modification, and Figure 11 is an end view of the same. Figure 12 (Fig. 19) is a side view and section of an improved form of motor, and Figure 13 is a section of a modified form of field coil, Figure 14 is a partial section of an improved form of field magnet, and Figure 15 is

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[44] Spec. U. S. Patent, No. 363,186. Filed January 26, 1887.

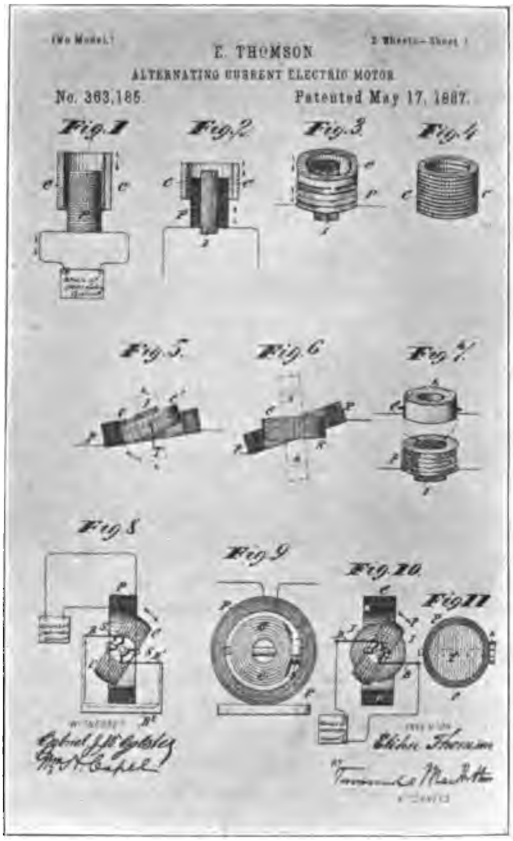

FIG. 18.

a partial section on a line parallel to the shaft of the machine. Figures 16, 17, 18, and 19 illustrate other modifications." He further says in this connection: "What I claim as my invention is—

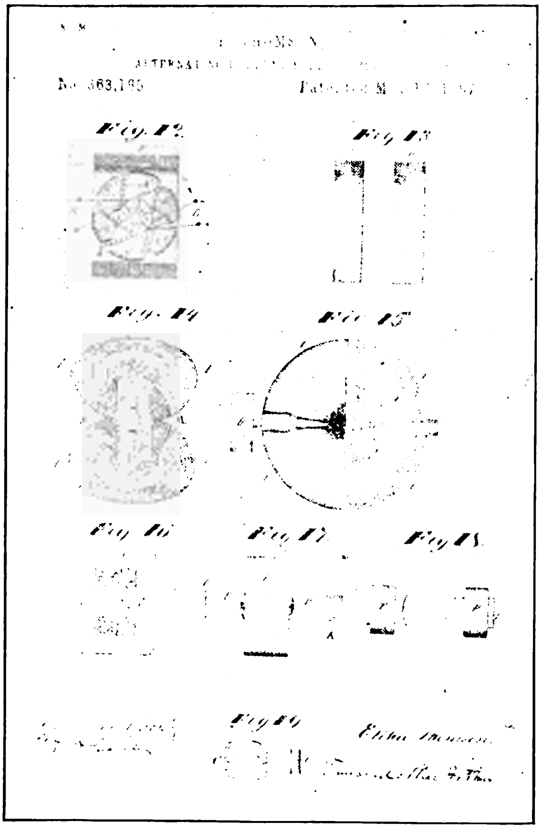

FIG. 19.

"An electric motor consisting essentially, of a means for producing rapid alternations of magnetic field, a low resistance conductor, or a coil of good conducting metal in which currents of high self-induction may be induced by said alternations, and a commutator for alternately closing and breaking the circuit of one or the other member as the parts move into and out of inductive relation to one another.

The second of these patents is described[45] as an "alternating current motor device," and in Fig. 20 Figures 18, 19, 20, 21, 22, illustrate various applications of this device, while Figures 23, and 24, show a rotary electric motor embodying the invention.

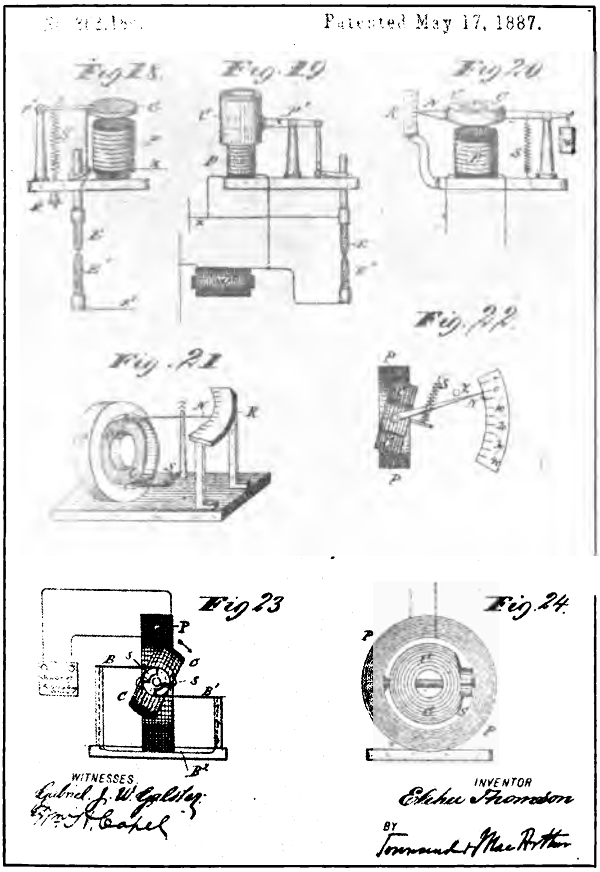

FIG. 20.

It will readily be seen that the second patent depends fundamentally upon the principle set forth in the first.

The invention of an alternating current motor by William Stanley, Jr.,[46] in 1887 is illustrated in principle by diagram

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[45] Spec. U. S. Patent, 392,471. Filed Dec. 9, 1887.
[46] Spec. U. S. Patent, 392,471. Filed Dec. 9, 1887.

(Figure 21) and consisted of "a field magnet with coils for magnetizing the same, an armature, a source of alternating currents, a commutator through which the currents are delivered to the field magnet coils, a supplemental circuit, applied to the field magnet for polarizing the same, a continuous current generator upon the armature shaft, and connections from said generator through the supplemental circuit."

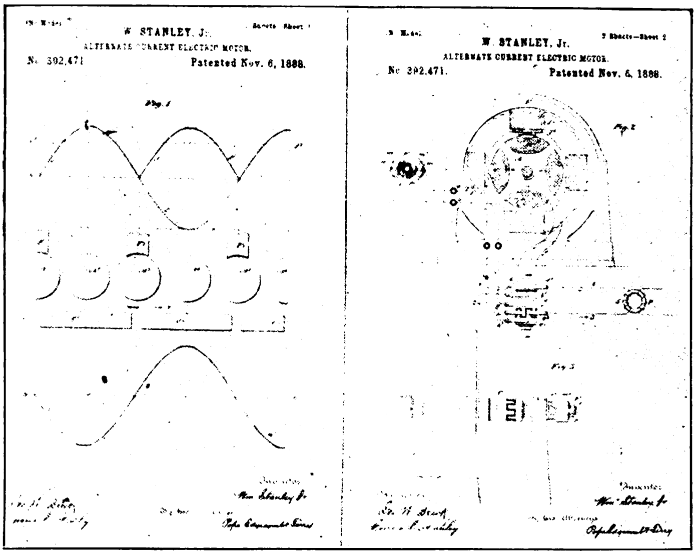

FIG. 21.

Figures 1 and 2 (Figure 22) illustrate a type of alternating current motor patented by William Anthony,[47] Dugald C. Jackson and Harris J. Ryan, in 1888, which also embodies the commutation of alternating current, yet differs quite materially from the Stanley machine. The claim for the invention is, "The combination, with the field magnets of an electric motor of an armature having its armature coils permanently included in a closed circuit, a commutator having its plates connected with different points in the length of the armature coils, and a closed circuit electrically uniting the brushes to said plates. (Fig. 1.)

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[47] Spec. U. S. Patent, 389,352. Filed Feb. 24, 1888.

The combination, with the field magnets of an electric motor, as above, and a closed circuit electrically uniting the brushes to said plates, and supplemental field-magnet coils applied to the field-magnet and included in the circuit uniting said brushes." (Fig. 2.)

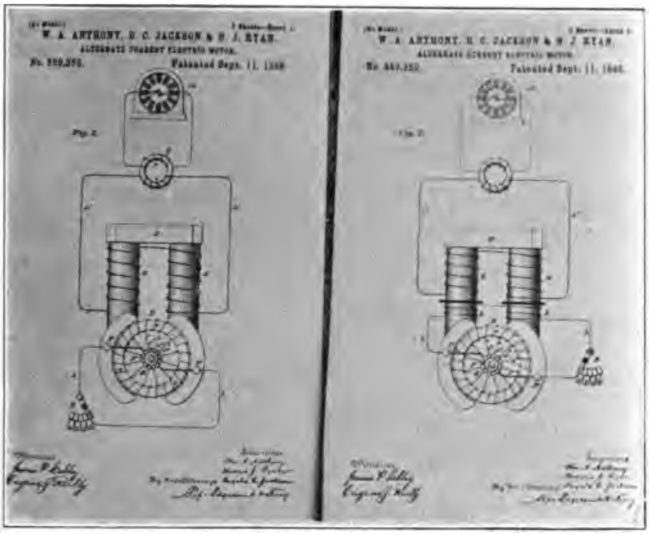
W. A. ANTHONY, H. C. JACKSON & H. J. RYAN.
W. A. ANTHONY, H. C. JACKSON & H. J. RYAN.

FIG. 22.

We now turn to Galileo Ferraris, of Turin,[48] who, it is said, constructed a motor on the principle shown in diagram by figures 23, 24, and 25, in 1885, though his apparatus apparently was not publicly exhibited and described until 1888. In the month of March, 1888, he presented to the Academy of Science of Turin, a Memoir on Electrodynamic rotations, in which he expounded the theory of the rotating field, and suggested that a simple method of producing two phase currents would be to divide the circuit carrying an alternating current; in one branch insert a non-inductive resistance coil, and in the other a low resistance coil of high self-induction. Such an arrangement he thought would give a difference of phase sufficiently near 90 degrees to produce a rotating field, with which might be obtained all the effects produced by the rotation of a magnet.

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[48] "Rotazioni elettro-dynamiche." Turin Acad., 1888.
London Electrician, May, 1888.

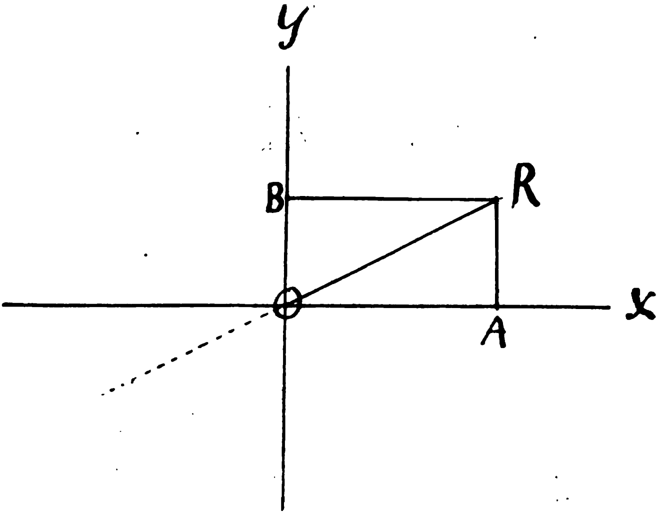

FIG. 23.

The action of his motor is explained as follows: In Figure 23, let the strength of two magnetic fields be represented by two vectors OA and OB, then the combined force exerted on a unit pole placed at O, would be given by the line OR or, in other words the two fields combine thus to give one field represented in direction and magnitude by OR. If both fields undergo periodic variations of the same period, the resultant field OR will undergo a periodic variation and the point R will trace a curve the form of which depends upon the precise manner in which the lines OA and OB change with the time. If the alternating currents are expressed as sine functions of the time the point R describes a circle about O when there is a lag between the currents in the two coils of 90 degrees; when the lag is greater or less than 90 degrees but greater than 0 degrees, the curve traced by R is an ellipse; and as the lag approaches 0 degrees or 180 degrees the ellipse grows flatter, approaching a mathematical line which it reaches in fact when the difference in phase, or lag between the two currents, is actually 0 degrees; then the point R performs harmonic oscillation over the line OR and its prolongation with O as a centre.

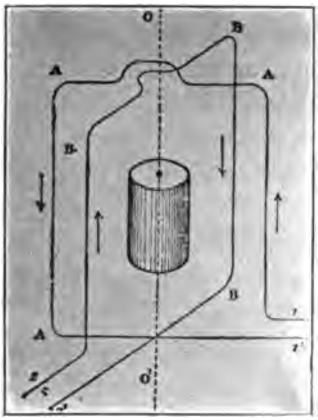

FIG. 24.

The application of this simple principle by Ferraris is evident from Figure 24, in which the two coils are AAA and BBB, connections being made by the wires 1,1′ and 2,2′. When alternating currents are sent through these coils a resultant field is produced which revolves around the line OO_1. In the centre between the coils is suspended a light hollow cylinder of copper, and as the lines of the resultant field cut the metal, eddy currents are induced, and by the interaction of these induced currents and the revolving field the cylinder is set in rotation; this is, obviously, just the reverse of the experiment in which the rotation of a copper disk beneath a magnet needle, deflects it in the direction of rotation of the disk, until ultimately the needle rotates synchronously with the disk.

Ferraris showed that the rotation could be produced either by introducing two phase current into the coils, or by splitting the phase of a simple alternating current by means of a transformer; i. e., the current from the machine traversed the primary of the transformer and also coil A, while the secondary current of the transformer passed through coil B, thus giving a phase difference between the two coils approximating 90 degrees though of course always greater than that value; still another method, was to use a transformer with two secondaries, in one of which was placed A, and a non-inductive resistance, and in the other B, and a coil of high self-induction.

Professor Ferraris after preliminary trials with a light copper cylinder, used one weighing 11 pounds (Figure 25). A test of this apparatus was made with a small friction dynamometer which showed a maximum output of 2.77 watts, at 650 r.p.m.

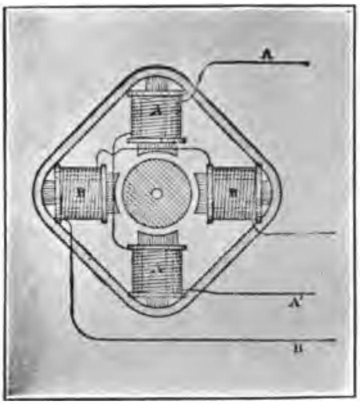

FIG. 25.

He presumed, however, that the chief use of the principle would be in the construction of meters for measuring alternating currents, and indeed it was so used at a later date in O. B. Shallenberger's meter. This well known apparatus has a coil through which flows the current to be measured, and a second short circuited coil so placed that the magnetic axes of both include an angle of 135 degrees. A current is induced in this second coil, and in accordance with transformer principles the relative intensity of the primary and secondary currents in this case are approximately as $\sqrt{2} : 1$ and the phase difference between them equal to 135 degrees. Here it may be seen that the amplitudes of the two component fields cannot be equal, and the phase difference of 135 degrees does not represent the angle between the two components, so that the oscillation curve is a stretched ellipse. This result is shown to be true of all motors, in fact, wherein but one current is used to produce a rotary field, whether by the first or second of the Ferraris methods, or by both combined as in some of the Tesla motors to be described.[49]

One of the early pioneers of alternating current work in this country was Charles Schenck Bradley,[50] whose first work dates from 1887. A patent filed by him May 8, 1887, describes a Gramme ring generator with symmetrical points on its armature connected to four slip rings, giving alternating currents differing in phase by 90 degrees. Claim 9 on this patent is, "A rotary electric motor consisting of a field magnet and an armature and pairs of current leading devices,—such for instance as contact rings and brushes—the respective pairs being independently connected into the armature winding at alternating points of the same, and arranged for connection with two independent external circuits."

In May, 1888, Nikola Tesla[51] (Servia, 1857- ——) read a paper before the American Institute of Electrical Engineers on "A New System of Alternate Current Motors and Transformers."

Just previous to this time a number of patents which had been pending in the U. S. Patent office since Oct., Nov., and Dec., 1887, were issued to Tesla, concerning numerous points of a fundamental character concerning alternate current rotations.[52]

This work appears to mark the beginning of a thoroughly practical application of the transmission and transformation of power by alternating currents. In this paper casual reference was made to two special forms of motors not directly considered.

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[49] For deductions concerning the rotary field see Electrical World, Vol. XVII, p. 477, A. Du Bois-Reymond. La Lumiere Electrique, Vol. L, p. 358.

[50] Spec. of U. S. patent 390,439.

[51] Inventions, Researches, and Writings of Nikola Tesla, Martin, 1894.

[52] Spec. of U. S. Patents, Nos. 381,968, 382,279, 382,280, 382,281, 382,282, May 1, 1888.

1. "A motor with one of its circuits in series with a transformer, and the other in the secondary of the transformer," and

2. "A motor having its armature circuit connected to the generator, and the field coils closed upon themselves."

The first of these it will be seen, directly embodies the Ferraris principle already described.

A quotation from a lecture by Tesla illustrates his early notions concerning commutating machines. He says: "In our dynamo machines, it is well known, we generate alternate currents which we direct by means of a commutator—a complicated device, and, it may be justly said, the source of most of the troubles experienced in the operation of machines. Now, the currents so directed cannot be utilized in the motor, but they must again by means of a similar unreliable device—be reconverted into their original state of alternate currents. The function of the commutator is entirely external, and in no way does it affect the internal working of the machines. In reality, therefore, all machines are alternate current machines, the current appearing as continuous only in the external circuit during their transit from generator to motor. In view simply of this fact, alternate currents would commend themselves as a more direct application of electrical energy, and the employment of continuous currents would only be justified if we had dynamos which would primarily generate, and motors which would be directly actuated by such currents."

But the operation of the commutator on a motor is twofold—first, it reverses the currents through the motor; and, secondly, it effects, automatically a progressive shifting of the poles of one of its magnetic constituents; it was a question how to produce the latter effect without it, that engrossed the attention of Mr. Tesla.

The accompanying Figure (26) illustrates diagrammatically the chief features covered by his early patents. Figure 9 in the series represents a specially wound generator used by Tesla, connected to a motor embodying his invention. The generator consisted of an ordinary two pole magnet frame with a drum armature with the two coils wound over it at right angles and connected to slip rings, thus giving two alternating currents differing in phase by 90 degrees. The motor field, made up of circular iron plates, was wound with four coils, each two opposite coils being so joined as to produce free poles opposite each other. Connection was made to the slip rings so that the field was formed of two independent circuits. Within the field was pivoted as a rotor a disk of iron, and when the two phase current from

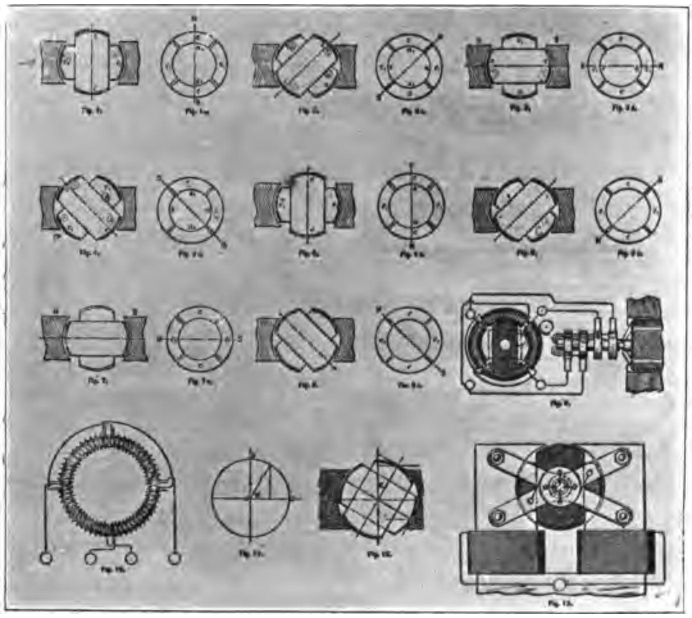

FIG. 26.

the generator passed through the motor field the iron was set revolving. Mr. Tesla attributed this phenomenon to a certain magnetic inertia, or resistance to the shifting of the magnetic lines. By the first series of eight consecutive figures (Fig. 26) Tesla explained the successive phases through which the coils of the generator pass during one revolution, and the corresponding and resulting changes of magnetism produced in the ring of the motor, the general idea being that the resultant direction of the magnetic field moves progressively around and exerts a corresponding drag upon the iron disk. This constitutes the simplest form of synchronous motor.

"Obviously, the rotation of the poles produces inductive effects and may be used to generate currents in a closed conductor placed within the influence of the poles. For this purpose it is convenient to wind a ring with two sets of superimposed coils, forming respectively the primary and secondary circuits. In order to secure the most economical results, the magnetic circuit should be completely closed as shown in Fig. 10, Fig. (26). If the intensity of the poles is kept constant, the same result will be obtained upon the armature coils as would be effected by a commutator having an infinite number of segments. In this case the relation between the primary coils and their magnetizing effect can be expressed by the equation to a circle with its centre coinciding with that of an orthogonal system of axes, where the radius is the resultant and the coordinates both of its components. These are sine and cosine of α Fig. 11, Fig. (26), and we have $r^2=x^2+y^2$; where $x=r \cos \alpha$ and $y=r \sin \alpha$.

"Assuming the magnetizing effect of each set of coils in the transformer to be proportional to the current, then $X=KC$ and $Y=KC_1$ where K is a constant and C and C_1 the current in both sets of coils respectively. Supposing further the field of the generator to be uniform, we have for constant speed $C_1=K' \sin \alpha$ and $C = K' \sin (90^\circ + \alpha) = K' \cos \alpha$ where K′ is a constant, Fig. 12. in Fig, (26), therefore

$$X = KC = KK' \cos \alpha$$
$$Y = KC_1 = KK' \sin \alpha$$
$$KK' = r$$

so that for a uniform field the two coils at right angles, is theoretically correct and the intensity of the shifting poles is constant."[58] But from $r^2=x^2+y^2$ it follows that for $y=o$, $r=x$, and the magnetizing effect of both coils should be equal to one at its maximum value. Figure 13, in Fig. (26), represents a

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[58] London Electrician, June 15, 1888.

Tesla device wherein the two poles are energized by induced currents when two phase currents are used in rotating the armature.

The principle of slip was stated in U. S. Patent No. 382,279, in which specification it is also shown that the direction of rotation may be reversed by *reversing* the connections of one of the circuits to the motor.

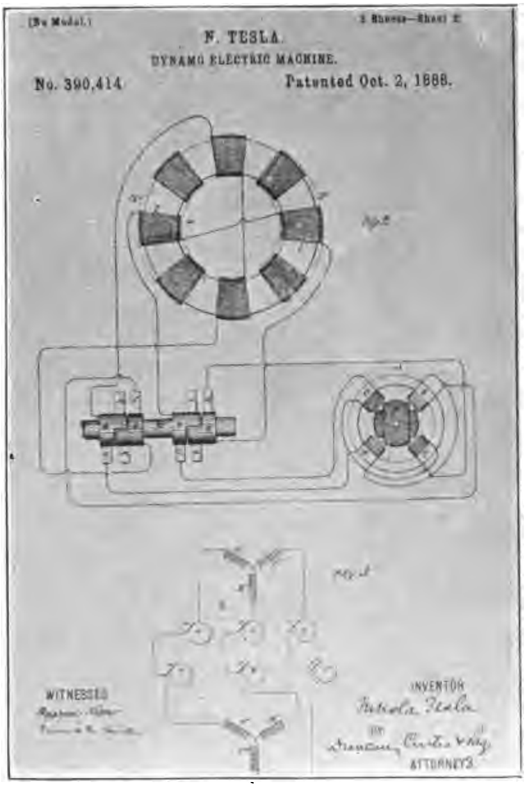

FIG. 27.

The next invention of interest in this connection was also one of Tesla's[54] and is shown diagrammatically in Figure 27. A part of his claim for the patent in explanation of the figure is as follows: "The combination, with a converter having independent energizing coils, of a continuous or direct current dynamo, or magneto machine, and intermediate circuits permanently connected at suitable points to the induced or generating coils of the generator. The combination, with a converter provided with independent energizing circuits, of a continuous or direct current generator provided with continuous collecting rings connected in derivation to the armature coils to form the terminals of circuits corresponding to those of the converter." It should be said here that so far as the descriptive matter in the patent states, and the diagram of connections shows, there is apparently only an illustration of the dynamo of Bradley[55] connected to a Tesla motor.

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[54] Spec. U. S. Patent, 390,414, Oct. 2, 1888.

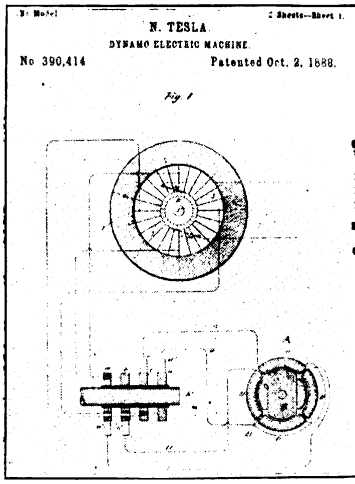

FIG. 27a.

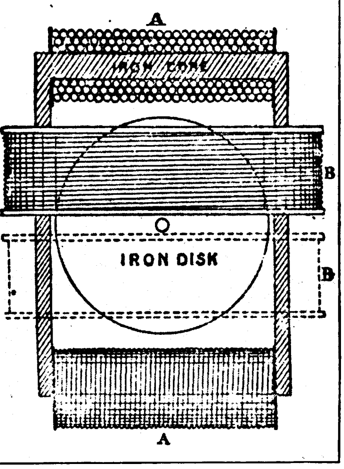

FIG. 28.

The next patent in order to be considered is that of Francois Borel, and Emile Paccaud,[56] whose application was filed Jan. 30, 1888. This device was manufactured as the Borel-Paccaud meter. It had two coils A A (Fig. 28), on an iron frame, and two other coils B B, outside the frame for producing a second field at right angles to the first. An iron disk was pivoted inside the coils as shown, and set in rotation by their combined influence.

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[55] Spec. U. S. Patent, 390,439, May 8, 1887.

[56] Spec. British Patent, 1383, 1888.

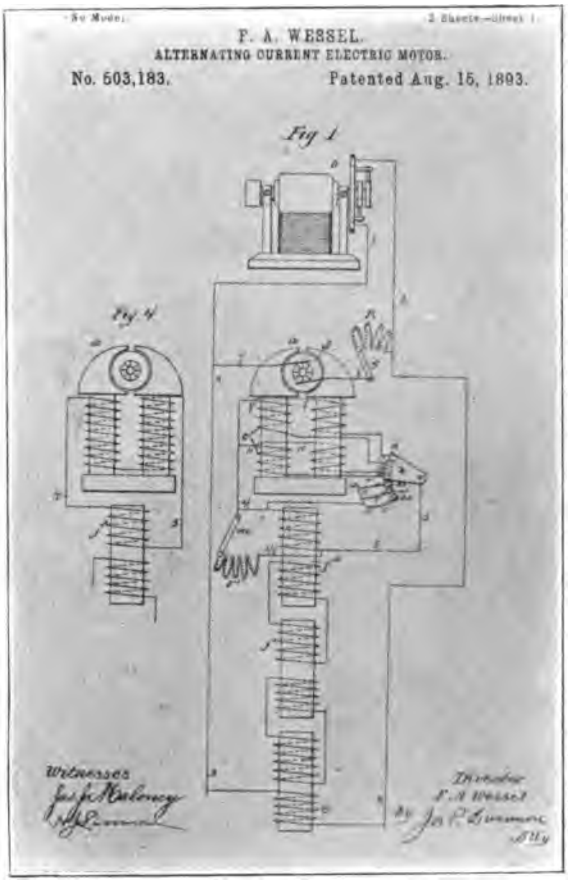

FIG. 29.

The substance of their claim is an "Apparatus having two parts both magnetized by coils in which alternating currents pass producing alternating polarities which attract and repel, whilst in one of the parts also such alternating polarities are produced in successive positions advancing step by step around the part and so making the circuit thereof whereby rotation is continuously maintained."

Ferdinand A. Wessel,[57] of Boston, filed an application on April 3, 1888, for U. S. Patent on a type of alternating motor

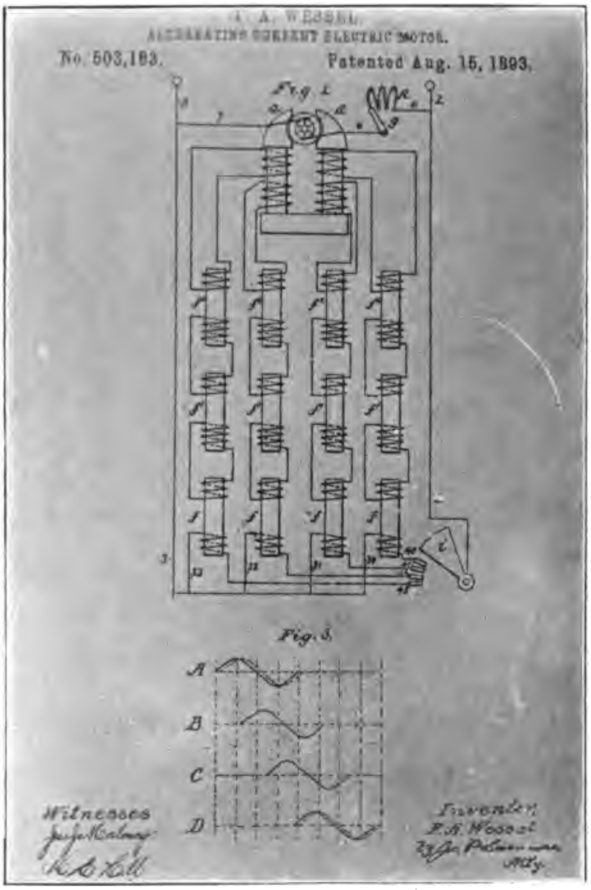

FIG. 30.

which appears to be simply the counterpart of the Anthony, Jackson, Ryan machine for which application for patent had been filed two months before. The illustrations, Figures (29, 30) show the principle upon which its action is based quite perfectly and so no detailed description need be given here, though one section of the claim runs thus:

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[57] Spec. U. S. Patent, 503,183, Aug. 15, 1893.

"The combination with the main leads for supplying an alternating current, of an electric motor having a continuous current armature and commutator therefor of any usual type supplied with alternating currents, from said leads, an alternating field magnet for said motor energized by said main and having its coils in a circuit separate from the armature, and one or more induction coils or converters having a primary coil connected with the main leads and a secondary connected with the coil of a field magnet, and adjusted as described to cause alternations synchronous with those of the armature."

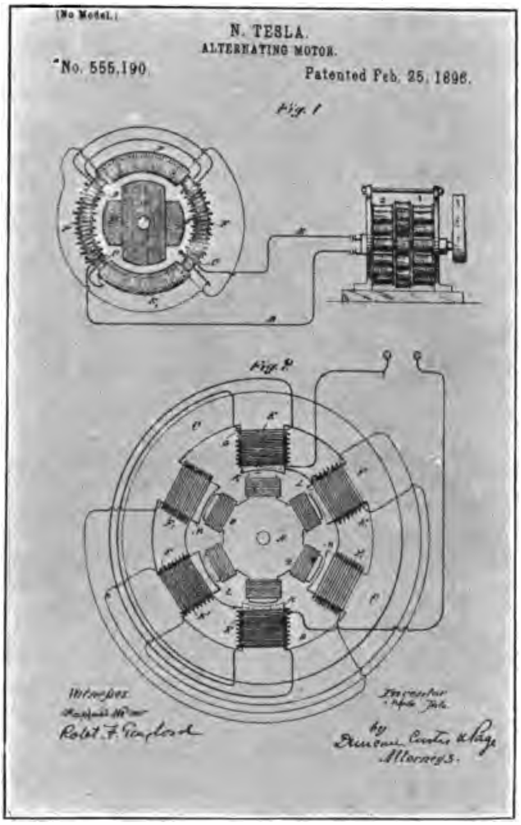

FIG. 31.

Following Wessel again comes an invention by Tesla,[58] filed under date of May 15, 1888, which is described as an electric motor having the combination of independent energizing circuits, one adapted to be connected with a source of alternating currents, the other arranged in inductive relation to the first whereby the motor will be operated by the resultant action of the two circuits as shown by diagram (Fig. 31).

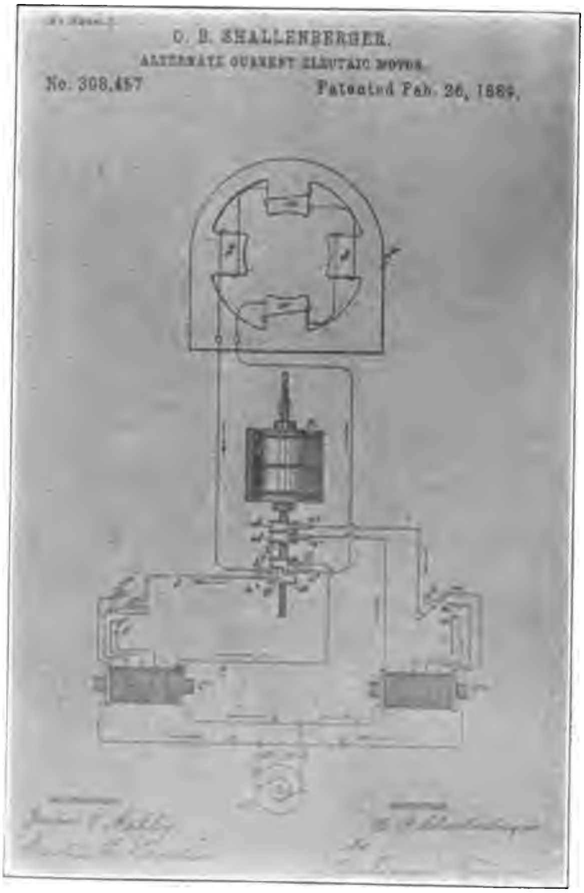

FIG. 32.

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[58] Spec. U. S. Patent, 555,190, 1896.

In Figures 32 and 33 is shown an alternating current motor devised and patented by Oliver B. Shallenberger[59] which is different from some already described only in some details. It consisted of "the combination, with the field magnet and armature of an electric motor, of a converter, having its primary coil supplied with alternating, intermittent or pulsatory currents and its secondary coil connected with the armature coils, and a second converter having its primary coil connected with a source

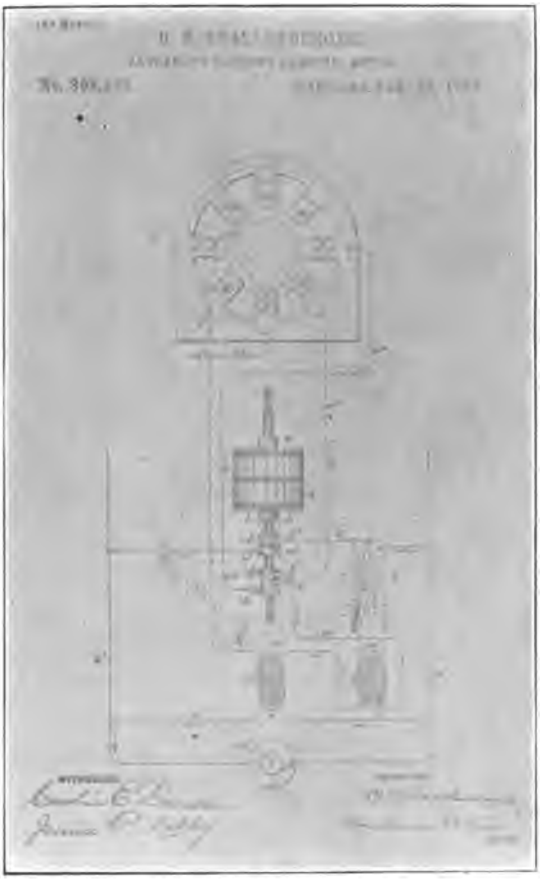

FIG. 33.

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[59] Spec. U. S. Patents, 398,457 and 398,458. Filed May 20, 1888.

of alternating currents and its secondary coil connected with the field magnet coils of the motor, and this is so proportioned that the lowest potential it can yield is suitable for the operation of the motor after it has attained a proper speed. When this speed is attained, however, the commutating device, through which the currents are supplied thereto, will serve to render continuous in direction the current delivered to the field magnet, while that delivered to the armature remains alternating." The apparatus was designed to "provide a motor which will start readily from a state of rest and gradually increase its speed

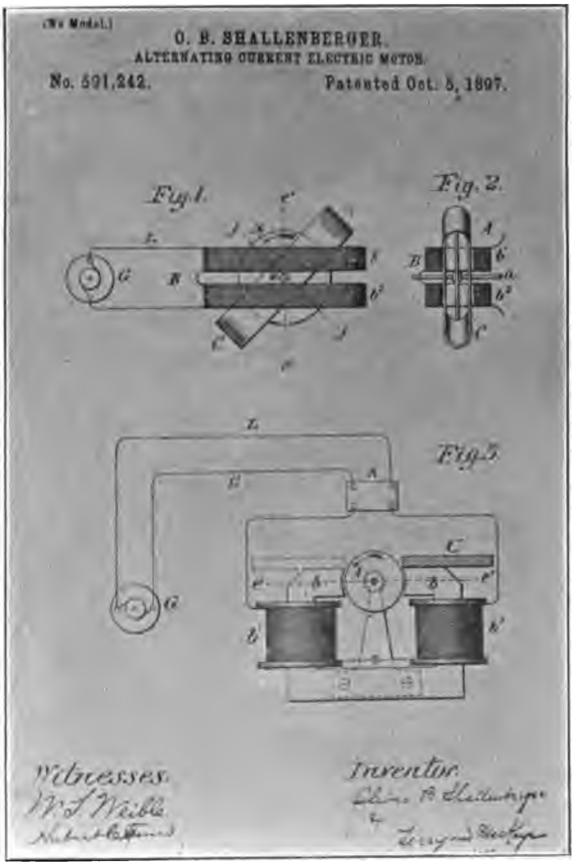

FIG. 34.

until it reaches a maximum dependent upon the rate of alternations of the electric current," and the Figures fully illustrate the connections for both patents which are quite closely related to each other.

Close upon the time of filing the application of these patents Shallenberger filed another, on June 7, 1888, though it was evidently not issued until several years later.[60] A part of his specification is indicative of the extent to which alternating currents were employed at that time; he says,

"The distribution of electric energy by alternating currents has now become well developed and has been introduced in extensive use for lighting purposes. No alternating current motor has yet been brought into public use, and the result is that no alternating current central station or plant has been able to supply power to consumers from its alternating current machinery, nor is it possible to use the conductors installed for such current for the distribution of both power and light. The object of this invention is to provide an alternating current motor which will be efficient in its operation, adapted to the various requirements of direct current motors, and which may be applied to the numerous alternating current plants now in general operation throughout the country, without requiring any change in the generators or circuits supplied thereby."

His claim (13) together with Figure 34 indicates the scope of the invention: "In combination, a rotating metallic armature, a coil in proximity thereto for inducing a polar line therein, and a second coil also in proximity to said armature so arranged as to have currents directly induced therein which currents induce, a second polar line at an angle with the polar line induced by the first coil."

In Figure 35 is shown the drawings of a repulsion alternating current motor, patented by E. Thomson[61] in 1889. The reaction between an alternating field and currents induced by such field in a closed circuit armature was the motive force.

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[60] Spec. U. S. Patent, 591,242, Oct. 5, 1897.

[61] Spec. U. S. Patent, 400,971. Filed July 30, 1888.

Supported upon a disk D, fixed to the shaft of the machine, is a ring I, of magnetic material having a number of coils A upon it, which are the closed circuit coils of the machine. By means of a commutator K, the circuit of each pair of coils A. A. in the same diametral plane is closed as the plane of these coils comes into parallel position with the coil C, which is the coil wound upon the alternating field and is in circuit with the source of alternating current for the machine. Figure 4 (in Fig. 35) shows a simple connection of the coils A. Figures 5, 6, and 7 show devices for regulating the operation of this machine.

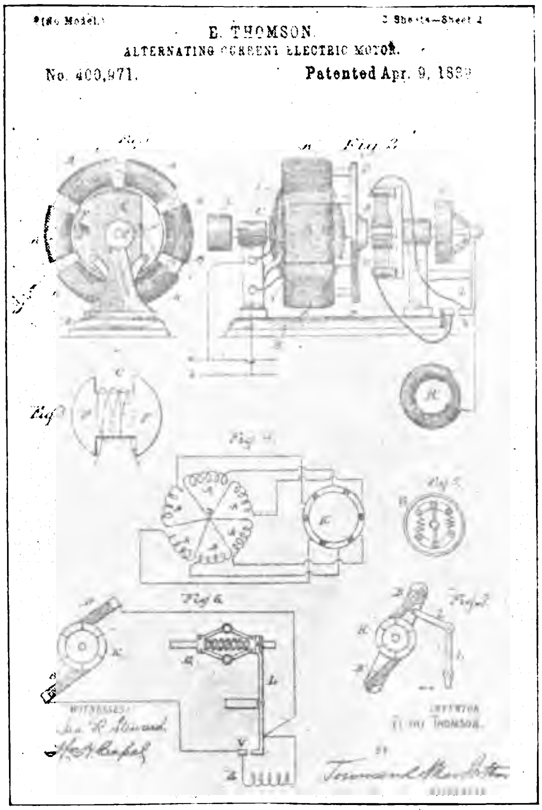

FIG. 35.

In October, 1888, Bradley[62] again appears for a patent on a synchronous motor driven by directed eddy currents in a stationary mass of iron and in which magnetic slip is fully explained. (Figure 36.) His claim in part runs as follows: "An electric motor comprising a field magnet adapted to be energized by the eddying current due to the rotation poles of the armature, in combination with an armature having magnetic poles rotating independently of its motion. In an electric motor, a rotary armature having independently rotating magnetic poles, in combination with a surrounding compound annulus, partly iron or steel and partly of a low resistance metal, the latter arranged in bars or sections parallel with the winding on the armature.

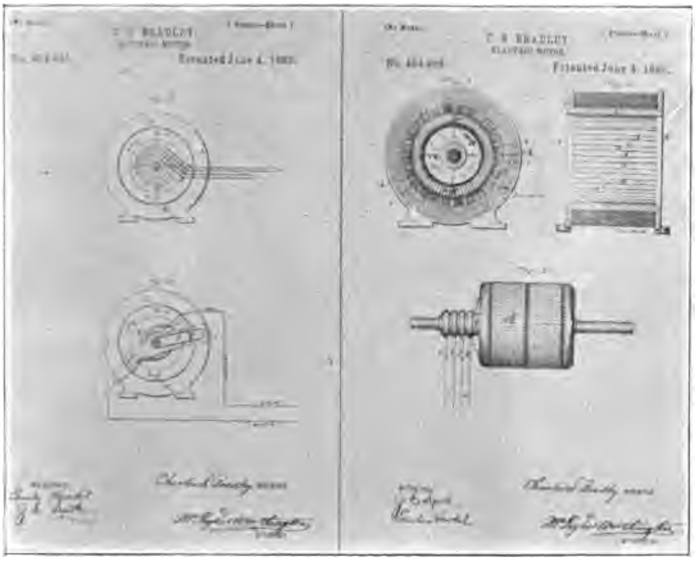

FIG. 36.

"A compound annular field magnet having its surface adjacent to the armature composed of alternate bars of iron or steel and a low resistance metal—such as copper or bronze—substantially as described whereby said low resistance bars form paths for currents.

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[62] Spec. U. S. Patent, 404,465, June 4, 1889.

"A compound annular field magnet having its surface adjacent to the armature composed of alternate bars of iron or steel and bronze, and having the ends of said low resistance bars connected to low resistance heads or cross-bars. A field magnet composed of alternate bars of magnetic metal and low resistance metal laid together to form a cylinder, and wound externally with iron or steel wire."

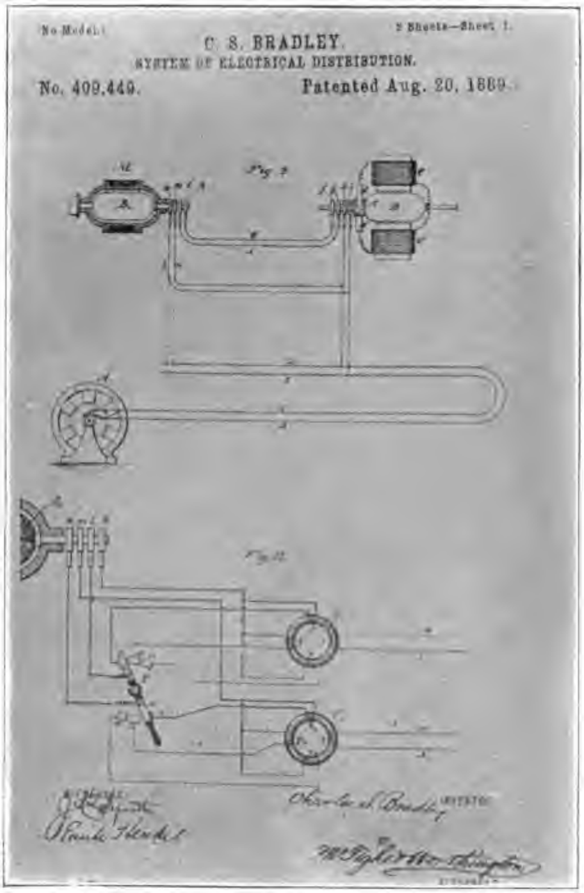

FIG. 37.

Another application by Bradley[63] on Oct. 5, 1888, indicates a method of splitting a single phase alternating current into two phases by the use of his machines. (Figure 37.)

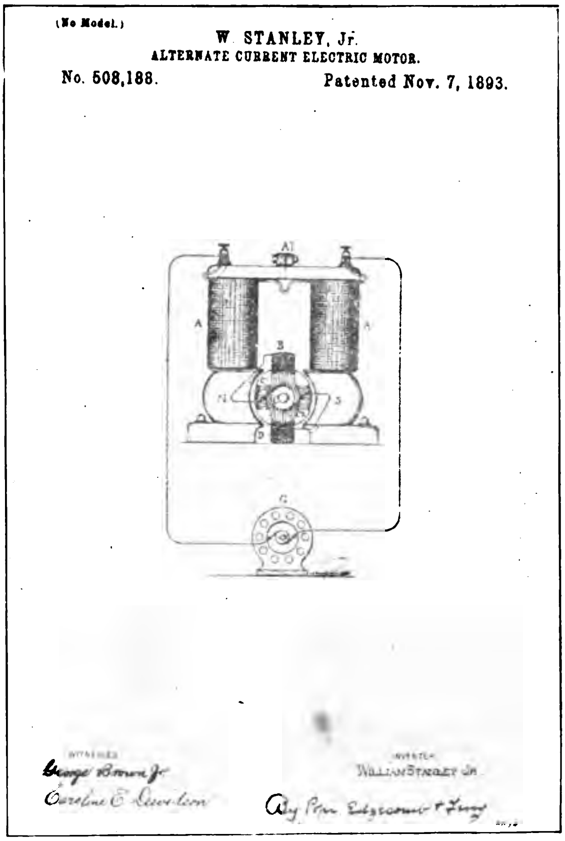

FIG. 38.

On Oct. 23, 1888, William Stanley Jr.[64] filed applications for two patents on alternating current motors the claims on which and Figures herewith indicate the principle of working involved. Figure 38 shows a diagram of the apparatus for one of these and the claim in part is, "In an alternating current motor the combination of an armature, the commutator, its brushes with which the terminals of the armature coils are connected, and a stationary independent magnetizing coil surrounding the armature, and having its plane at an angle to the plane assisting the polarizing effects of the armature coils."

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[63] Spec. U. S. Patent, 409,440.

[64] Spec. U. S. Patent, 568,188, Nov. 7, 1893. Spec. U. S. Patent, 591,301, Oct. 5, 1897.

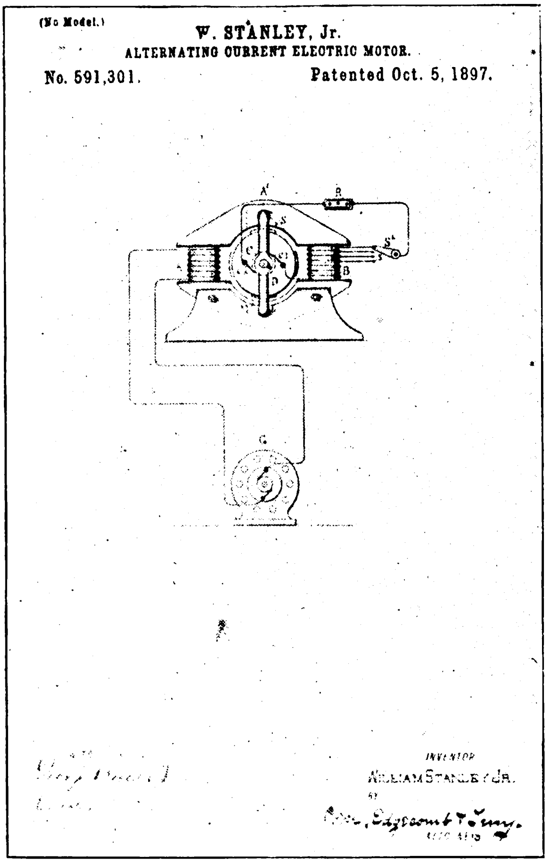

FIG. 39.

The other patent illustrated by Figure 39 claims, "An electric motor consisting of a field magnet having a closed core and having two coils, one adapted to be connected in series with a source of alternating currents, and the other acting as a secondary coil with reference to the first, whereby the effects of the current induced in the latter and the current flowing in the former

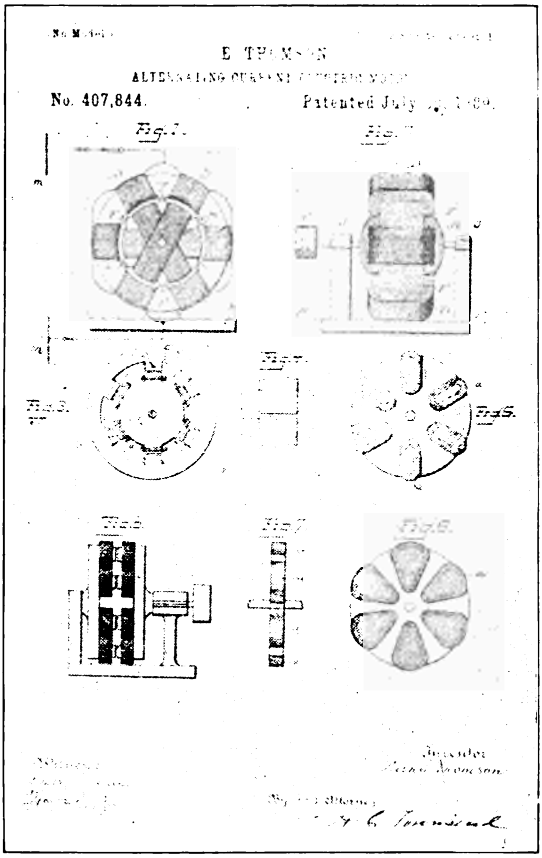

FIG. 40.

combine to establish poles in the field magnet core, and an armature in the field of force thus established, having its coils supplied with current from said second coil of the field magnet."

Closely following Bradley, on Nov. 17, 1888, Elihu Thomson[65] filed another application for a patent upon what is in fundamental principle the single-phase induction motor of the present time, without means for starting.

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[65] Spec. U. S. Patent, 407,844, July, 1889.

His specification says that the "invention provides a motor in which motive power may be developed by alternating currents on a single circuit, or by alternating currents the same in phase in the energizing coils of the motor, and does not require as do some previously invented alternating current motors, two circuits or sources supplying alternating currents of different or displaced phase in the energizing field.

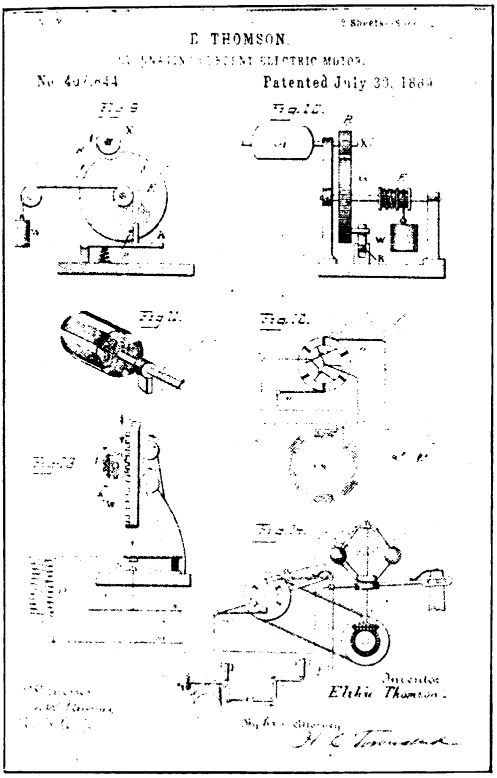

FIG. 41.

"Briefly," he says, "my invention consists in the combination of a set of energizing coils supplied with an alternating current of substantially the same phase in all the coils, and a set of coils inductively related to the first, and kept in a continually closed, preferably uncommuted, circuit while the motor is running, one or the other or both sets or systems of coils being movable as in ordinary electric motors." Combined with the motor are suitable devices for bringing the armature up to a moderate speed, determined by the rapidity of the alternations, after which its speed will increase continually until full speed or a speed almost synchronous with the rate of alternations supplied, is attained. The speed cannot go above synchronizing speed. (Figures 40 and 41.)

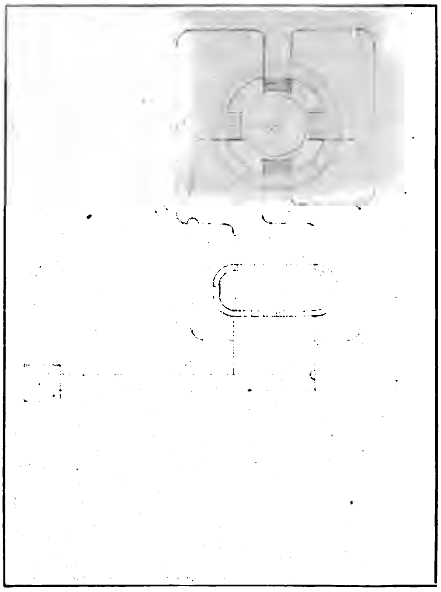

FIG. 42.

In two U. S. Patents filed by Tesla[66] on December 8, 1888, diagrammatically shown in Figures 42 and 43 respectively, are the following two claims with reference to the first:

1. "The method of operating motors having independent energizing circuits, as herein set forth, which consists in passing alternating currents through both of the said circuits and retarding the phases of the current in one circuit to a greater or

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[66] Spec. U. S. Patents, 511,559 and 511,560.

less extent than in the other. 2. The method of operating motors having independent energizing circuits, as herein set forth, which consists in directing an alternating current from a single source through both circuits of the motor and varying or modifying the relative resistance or self-induction of the motor circuits and thereby producing in the currents differences of phase as set forth."

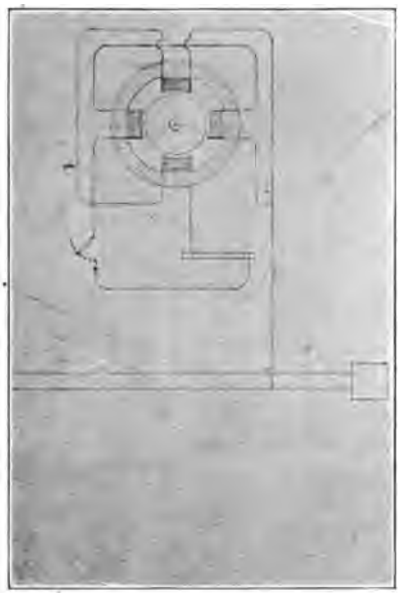

FIG. 43.

The chief claim of interest on the other patent is number 3 as follows: The combination with a source of alternating current and a circuit from the same, of a motor having independent energizing circuits connected in derivation or multiple arc with said circuit and of different active resistance.

In a U. S. Patent filed April 6, 1889, Tesla[67] described a combination of a synchronous with a non-synchronous motor whereby the latter should start the former, with a switch mechanism for directing the current through either of the motors separately or both at the same time. The diagrammatic scheme for this apparatus is given by Figure 44.

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[67] Spec. U. S. Patent, 459,772, Sept., 1891.

On April 16, 1889, Tesla[68] described the operation of two phase motors from a single phase line by splitting the phase, which was, of course, a practical application of the Ferraris arrangement described on page 35 of this paper. This was done as shown in Figure 45, by means of a non-inductive resistance coil R, and a choke coil L inserted in the circuit for starting. When the motor is at speed these coils are cut out by

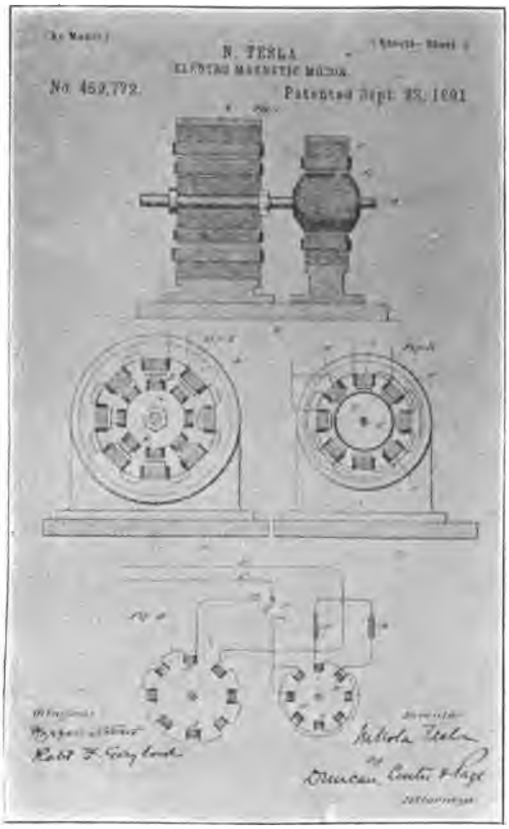

FIG. 44.

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[68] Spec. British Patent, 6,527, 1889.

means of the switch shown and the machine continues to operate as a synchronous motor. Of course this was by no means the first instance of split phase working as may be noted, but Tesla's claim is chiefly for a starting device for a synchronous motor.

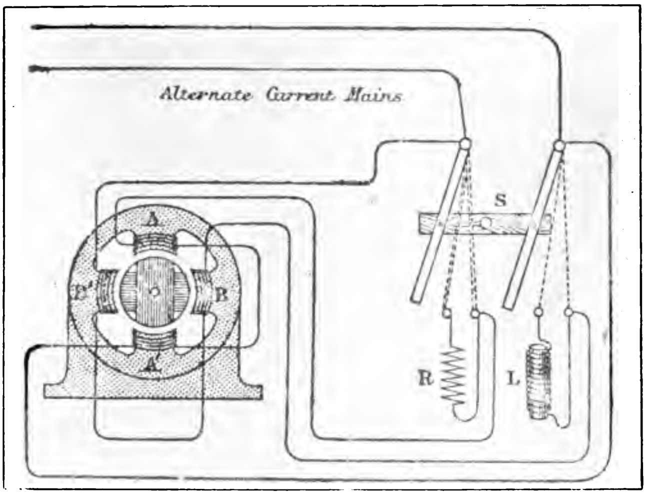

Fig. 45.

Close upon this patent follow several others by Tesla upon various forms of motors actuated upon the split phase principle, which will be briefly referred to in order of the filing of the applications.

The first three[69] upon May 20, 1889, are of the "magnetic lag" type and are illustrated by diagram. (Figs. 46 and 46a.) The claim of the first to be issued (416,193) indicates in substance the scope of the apparatus, and reads,—"In an alternating current motor having two or more energizing circuits the coils of one circuit being composed of conductors of large size or low resistance and those of the other of fewer turns of wire of smaller size or higher resistance," and "the combination, with long and short field cores of energizing-coils included in independent circuits, the coils on the longer cores containing an excess of copper or conductor over that in the others."

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[69] Spec. of U. S. Patent, 416,193. Spec. of U. S. Patent, 424,036. Spec. of British Patent, 19,420, Dec. 3, 1889. Spec. of U. S. Patent, 445,207, 1891.

The second one (424,036) is another form of "magnetic lag" motor which differs from the above in operation simply in "that the attractive effects or phases of the poles, while lagging behind the phases of current which produce them, are manifested simultaneously and not successively." (Fig. 46a.)

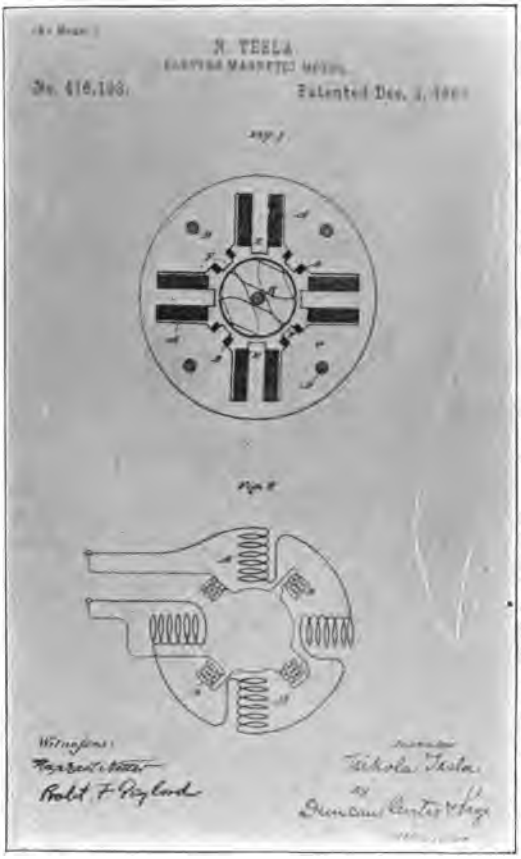

FIG. 46.

The third form is explained as follows: "In Figure 1 (Fig. 47) let A designate the field-magnet of a motor which is built up of sections or plates; BC, are polar projections upon which the coils are wound upon one pair of poles, as C. I wind primary coils D, which are directly connected to the circuit of an alternating current generator G. The currents in both primary and secondary coils in such a motor will be retarded or will lag behind the impressed E. M. F., but to secure a proper phase difference between the primary and secondary currents themselves I increase the resistance of the current of the secondary and reduce as much as practicable its self-induction. I do this by using for the secondary circuit, particularly in the coils E, wire of comparatively small diameter, and having but few turns

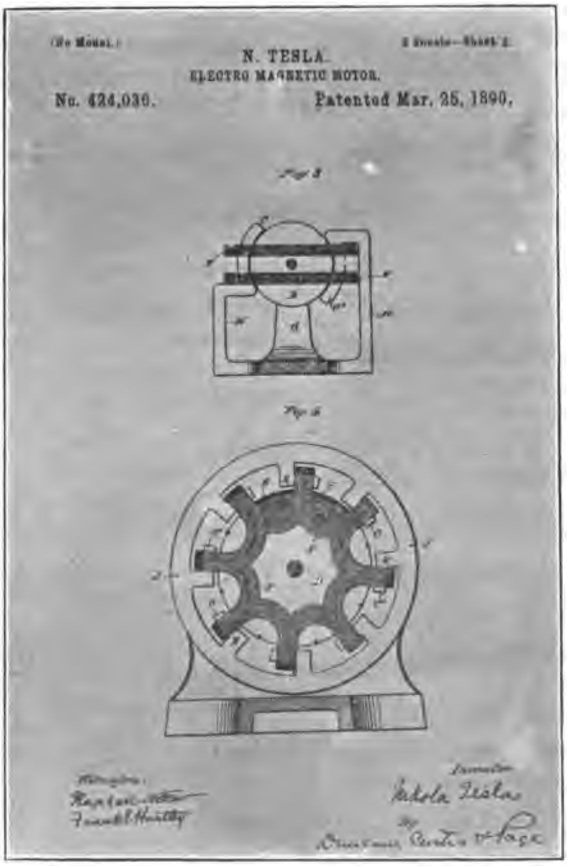

FIG. 46a.

around the cores; or I use some conductor of higher specific resistance, such as German silver; or I may introduce at some point in the secondary circuit an artificial resistance R. Thus the self-induction of the secondary is kept down and its resistance increased with the result of decreasing the lag between the impressed E. M. F. and the current in the primary coils and increasing the difference of phase between the primary and secondary currents." "In the operation of the motor the current impulses in the primary coils induce currents in the secondary coils, and by the conjoint action of the two the points of greatest magnetic attraction are shifted and rotated."

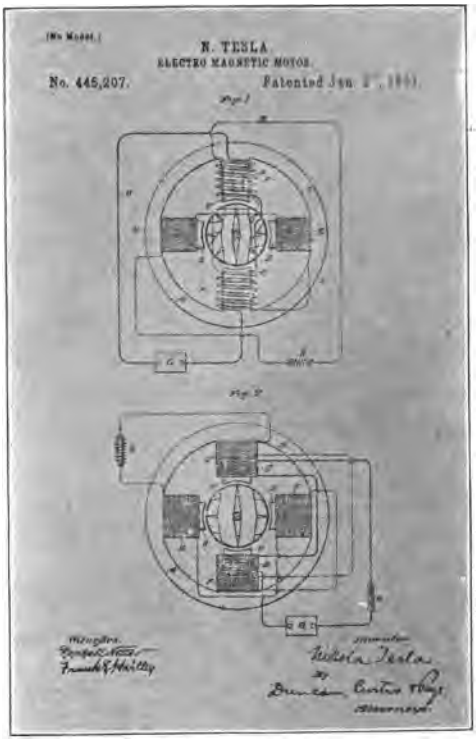

FIG. 47.

In the next application filed March 26, 1890, Tesla[70] says:

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[70] Spec. U. S. Patent, 433,700, Aug. 5, 1890.

"The improvements, subject of this application, are more particularly applicable to that class of motors in which two or more sets of energizing-magnets are employed and in which by artificial means a certain interval of time is made to elapse between the respective maximum periods or phases of their magnetic attraction or effect. This interval of difference in phase between the two sets of magnets, when artificially produced, is limited in extent.

"It is desirable, however, for the economical working of such motors that the strength or attraction of one set of magnets should be maximum at the time when that of the other set is maximum and conversely; but these conditions have not heretofore been realized except in cases where the two currents have been obtained from independent sources in the same or different machines."

"The object of the present invention is to establish conditions more nearly approaching the theoretical requirements of perfect working, or, in other words, to produce artificially a difference of magnetic phase by means of a current from a single primary source of practical and economical working."

"In carrying out my invention I employ a motor with two sets of energizing field magnets, each wound with coils connected with a source of alternating or rapidly-varying currents, but forming two separate paths or circuits. The magnets of one set I protect to a certain extent from the energizing action of the current by means of a magnetic shield or screen interposed between the magnet and its energizing coil." This shield is arranged so as to protect the main core from magnetization until it has become itself saturated, and so it is readily seen that the energizing action begins in the protected set of magnets a certain arbitrarily determined period later than in the other, and so in this way it is claimed that a "practically-economical difference of magnetic phase may readily be secured."

Figure 48 shows diagrammatically the disposition of apparatus and Figure 49[71] indicates a slight improvement in the same device. Another motor designed on the principle of "magnetic lag," is indicated by Figure 50. In this apparatus Tesla[72] takes advantage of the fact that the exterior portion of an iron core inside a coil carrying a current is magnetized appreciably sooner than the interior portion of the core. In Figure 1 (Fig. 50) X represents a large laminated iron core, and surrounding it a coil Y carrying alternate currents. When a magnetizing impulse is started in Y the part (a) being close to the coil is first energized, while the part (b) which is in a way protected by layers

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[71] Spec. U. S. Patent, 433,701, Aug. 5, 1890.

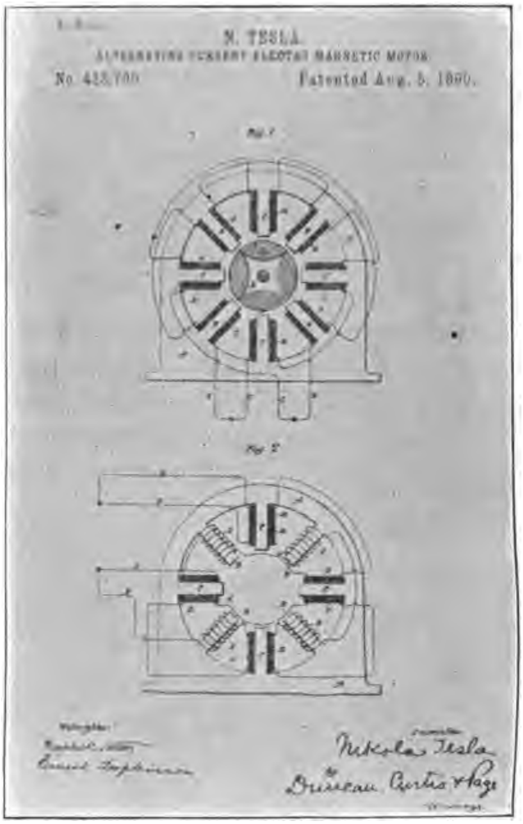

FIG. 48.

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[72] Spec. U. S. Patent, 433,703, Aug. 5, 1890. Filed April 4, 1890.

between it and (a), reaches its magnetic state a little later than (b) does. The result is with an alternating current that (a) may be reversed while (b) still continues its first polarity, and so it was found that if an armature (a simple disk) be arranged in proximity to the core, a movement of rotation was imparted thereto, and upon this principle was constructed a motor of the style shown in Figure 2 (Fig. 50).

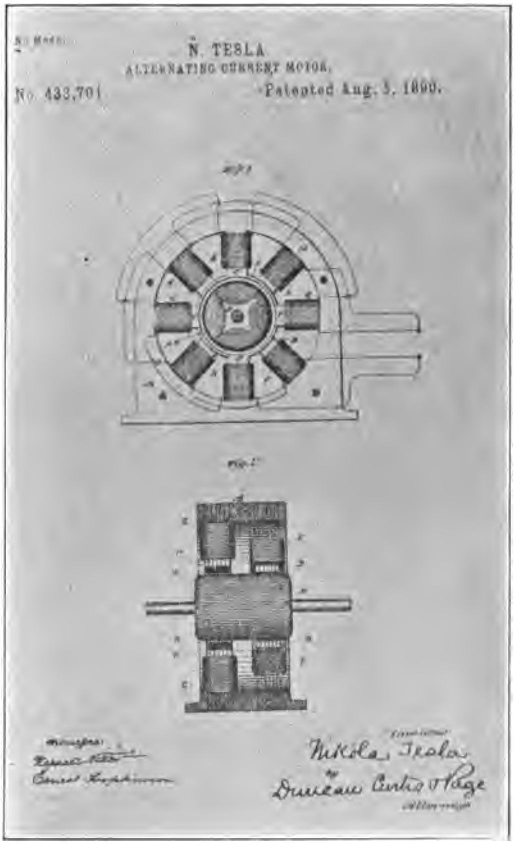

FIG. 49.

Maurice Hutin and Maurice Leblanc[73] filed an application Jan. 12, 1891, for a British Patent on an improvement in the operation of single phase motors in which they claim, "An alternate current dynamo electric motor wherein are combined an inductor or field consisting of two equal currents and so arranged that each pole resulting from the one is at equal distance from two successive poles of the other, a condenser or pair of condensers arranged to produce a difference of phase of a quarter of a wave in the currents for the two circuits, an armature consisting also of two circuits arranged like those of the field and two rheostats from the armature circuits having their resistance varied but always equal to one another."

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[73] Spec. British Patent, 584, Nov. 21, 1891.

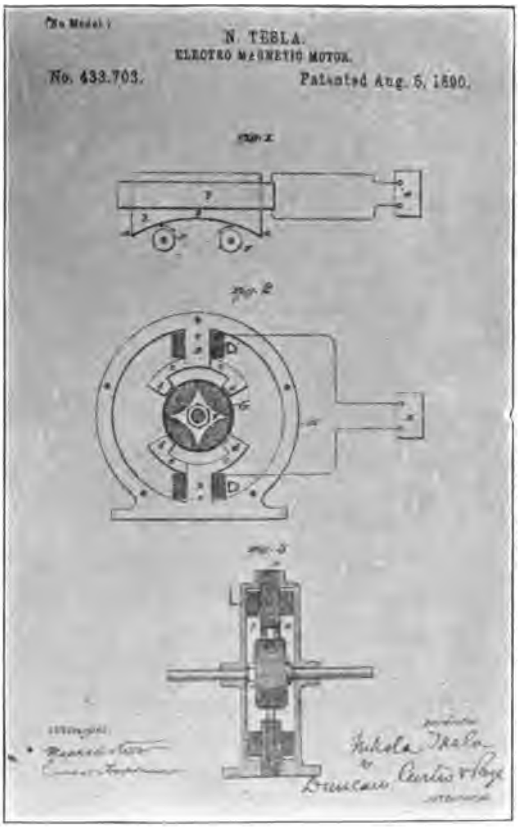

FIG. 50.

Tesla[74] follows with two more applications the first of which was filed on January 21, 1891, comprises an improvement in the running of a two phase motor which might of course be operated from single phase mains by some of the foregoing devices. The improvement had as its main feature the introduction of a condenser into the induced or armature circuit of the motor. (Fig. 51.)

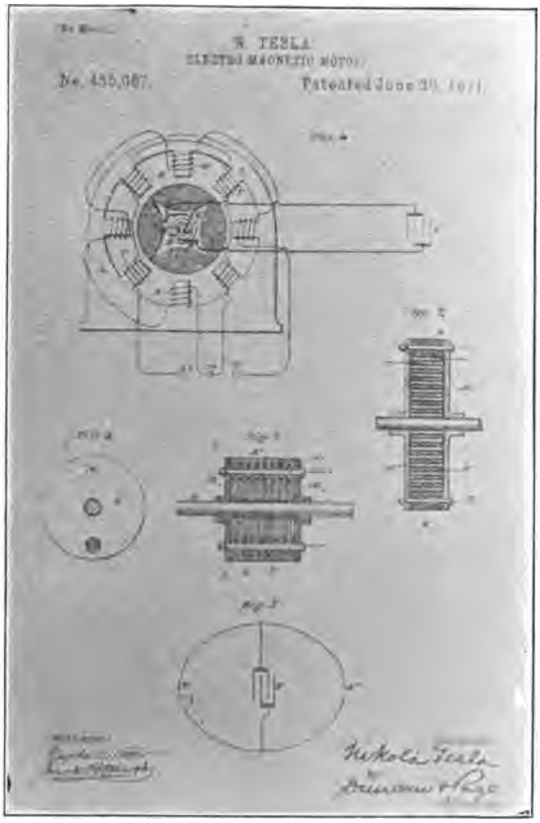

FIG. 51.

The other invention[75] filed July 13, 1891, is perhaps best described by a part of the claim which runs: "In an alternating current motor having two or more energizing field circuits one of which is adapted for connection with a source of currents, and the other or others in inductive relation thereto, the combination, with the secondary or induced circuit or circuits of a condenser interposed in the same."

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[74] Spec. U. S. Patent, 455,067.
[75] Spec. U. S. Patent, 464,666.

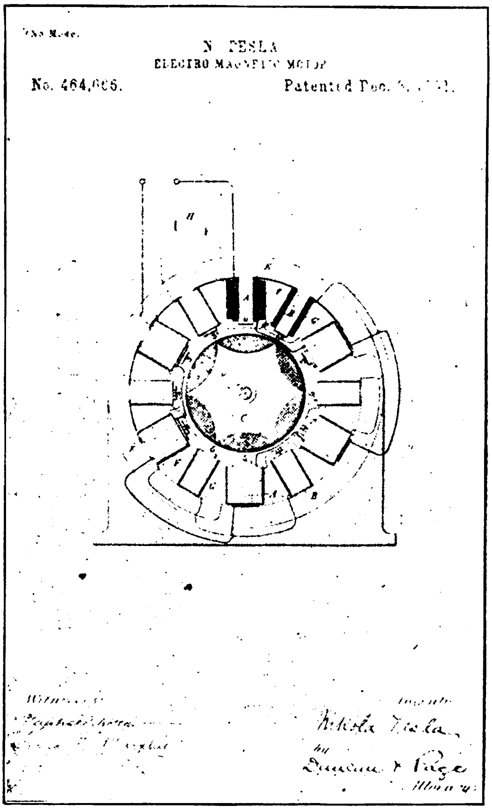

FIG. 52.

"In an alternating current motor the combination of two energizing circuits, one connected with a source of alternating current, the other a high potential secondary circuit in inductive relation to the first, and a condenser interposed in said secondary circuit." The arrangement of apparatus and connections is shown in Figure 52.

In April, 1891, Conrad L. Rosenquist[76] filed an application for an invention pertaining to alternating current power transmission, which appears to be of a more or less complex character, the patent upon which was not issued until 1899. His invention was for an alternating current motor provided with circuits and connections for both synchronous and non-synchronous rotation. The synchronous armature coils are connected through a commutative device to the supply mains, and when synchronous speed is attained an exciter driven by the armature of the motor supplies current to the fields. The circuit through the commutator and brushes is then opened and the motor operates as a synchronous motor.

From this time on for nearly two years it seems that the majority of the patents concerned with single phase motors, if not, indeed, all of the important ones, excepting Gutmann's, were taken out in foreign countries, of which only those recorded in Great Britain will here be considered.

Ludwig Gutmann's[77] single phase motor (Oct. 23, 1891), is described in part as follows: "The combination with a source of single phase alternating current, of a main armature winding adapted to be rotated through the influence of the current from said source, a supplemental armature winding, the coils thereof being connected in circuit with said main winding through which coils, currents from said main winding are adapted to be successively and periodically passed to produce biphase or polyphase currents, a commutator for commutating said biphase or polyphase currents, a field magnet adapted to rest upon the conductors carrying said biphase or polyphase currents, and coils for exciting said field magnet, said coils being included in circuit with said commutator." (Figure 53.)

Johann Sahulka[78] filed an application on July 15, 1891, for two improvements which he classified as,—

"1. The intensity of the rotary magnetic field is constant, and

"2. Such constancy is obtained not by increasing the number of conductors but by employing only one alternating current so that two conductors are sufficient." This really amounted to a split phase motor, using the secondary of a ring transformer as one circuit.

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[76] Spec. U. S. Patent, 619,620, Feb. 14, 1899.

[77] Spec. U. S. Patent, 530,178, Dec. 4, 1894.

[78] Spec. British Patent, 12,046, 1891.

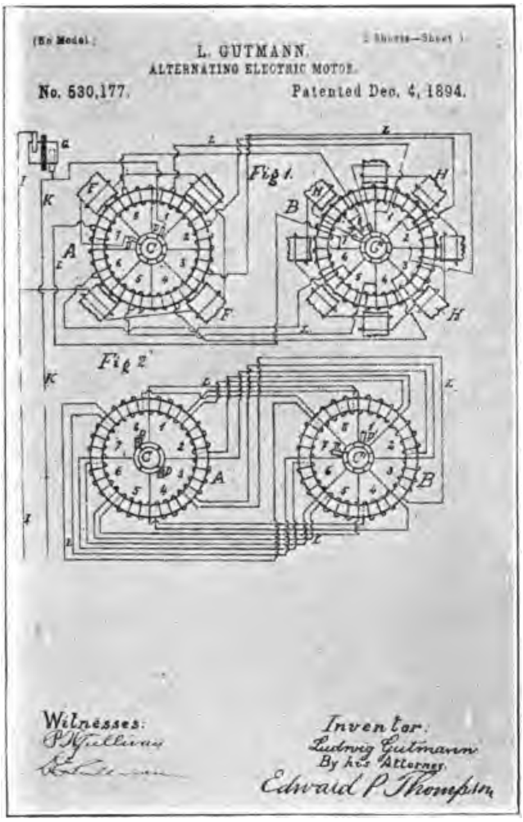

FIG. 53.

Following this came a number of patents dealing largely with so called improvements concerned chiefly with the application of commutating devices, and lamination of fields, in order to utilize in connection with alternating current, the fact that the direction of rotation of a direct current motor is the same regardless of the direction of the supply current. Among the more important of these were William Blanch Brain and Arthur

James Arnot,[79] William Stanley, Jr., and John Forest Kelly,[80] the latter having two in succession, the second of which[81] is indicated by diagram Figure 54.

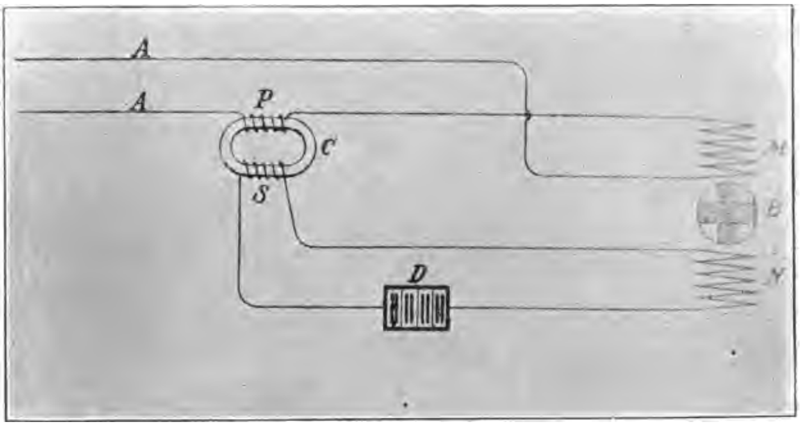

FIG. 54.

On Nov. 12, 1892, the Oerlikon Co.,[82] filed an application for patent on a monophase motor shown in diagram Figure 55. The claim is,

"1. A single phase alternating current motor having a series of exciting or inducing coils so arranged as to form an annular series of alternately north and south poles, each pole being composed of a series of similar poles of the same sign, and each pole being formed by an equal number of like coils connected in series or parallel; a series of armature or inductive coils consisting of two or more short circuited conductors which may be electrically connected together, or be arranged independently of each other, the arrangement being such that when the two series of coils are rotated relatively to each other, there will be induced in the conductor of the armature or inductive coils, current of different phases; and the total electro magnetic effect of these upon the exciting poles, represents a value different from zero as soon as the motor has acquired a certain initial speed.

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[79] Spec. British Patent, 13,627, 1891.
[80] Spec. British Patent, 20,604, 1891.
[81] Spec. British Patent, 14,056, 1892.
[82] Spec. British Patent, 20,505, 1892.

"2. A motor of the kind specified in the preceding claim, a device for starting the motor, said device consisting of wire especially wound upon the inducing part of the motor in a suitable position near the exciting coils and connected with a switch for the purpose of utilizing this special coil when the motor is being started; that is to say, before it has assumed a practically synchronous speed of motion, by forming in conjunction with

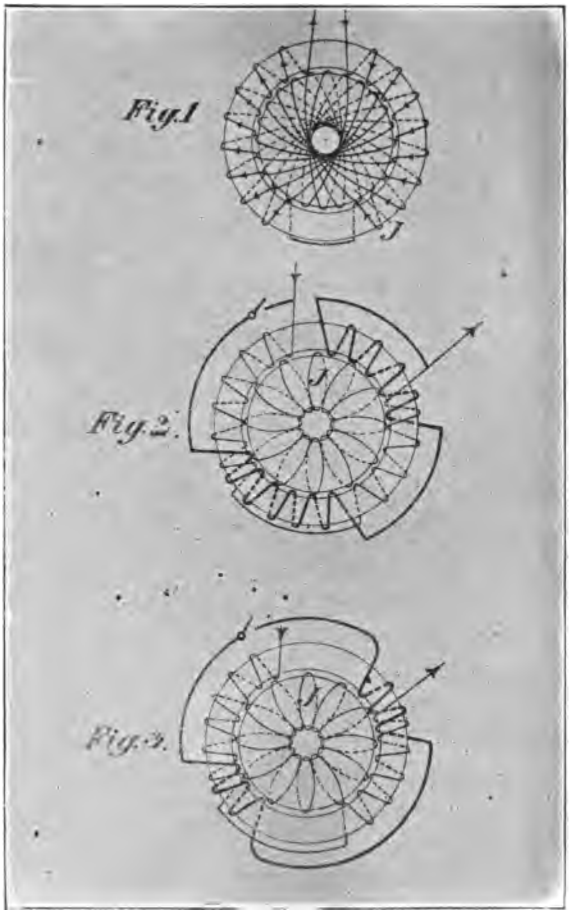

FIG. 55.

the exciting coils of the motor, a rotary field in the inductive part, and after starting the motor, or after switching off the current, the special wire can be used as a portion of the exciting coil."

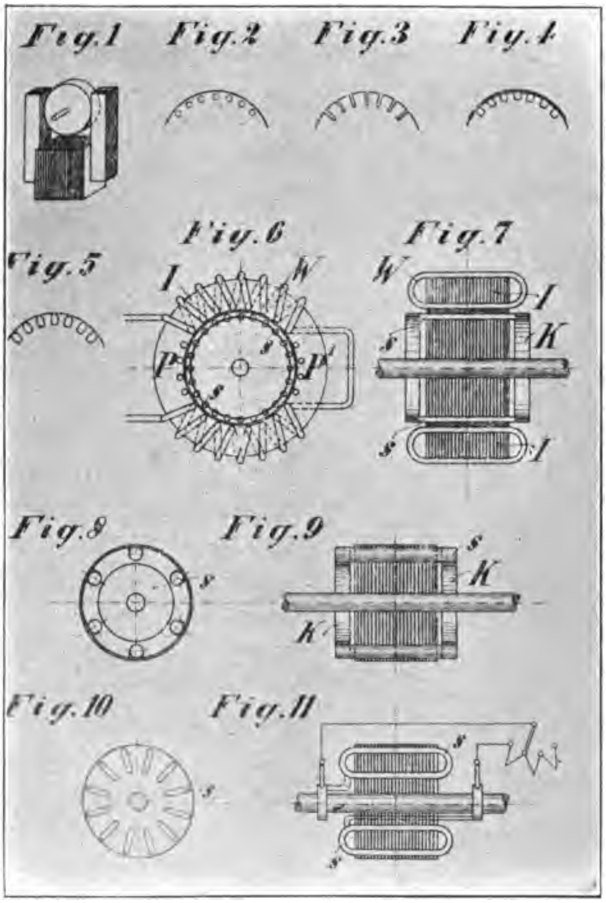

FIG. 56.

Charles Eugen Lancelot Brown[88] of Baden, Switzerland, who is well known to be prominent in the development of alternating current apparatus, and to whom is due the introduction of the vertical shaft type of generator which is so well suited to direct connections with the turbine, made application for a British patent concerned with single phase work on December 27, 1892.

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[88] Spec. British Patent, 23,902, Oct. 14, 1893.

This apparatus indicated by Figure 56, is an alternating current motor having its inductor winding adapted to be placed in direct connection with the service or supply mains and its induced winding in which currents are induced by the said inductor winding, short circuited on itself; it is for use with ordinary or single phase alternating current, having its winding imbedded in holes or apertures formed in laminated iron cores, for the purpose of reducing the magnetic resistance and, in consequence, the necessary exciting current to a minimum. The Figure shows the motor with the connections so made as to produce poles at P, P.′

In another specification filed Dec. 30, 1892, Brown[84] describes a number of methods of starting monophase motors, including those of self-induction and capacity, of using auxiliary windings, and of methods of connecting conductors in the rotor in such a manner as to produce in them a polarity inclined to that of the stator. In these the rotor is wound as an ordinary armature and has connections to a commutator as in direct current machines. Two opposite points of the winding are connected to two slip rings and when the motor is started a resistance is inserted between the brushes on the slip rings, and the brushes on the commutator are so placed as to short circuit some of the rotor windings which lie obliquely to the direction of the alternating flux of the stator. The short circuited coils having a large current turn into parallelism with the alternating flux, and so a continuous torque is produced. As the motor comes to speed the brushes may be moved apart till opposite each other, and the brushes on the slip rings are then also short circuited. Brown further uses some methods which take current to the rotor directly from the mains through a commutator at starting.

The next patents to be considered were filed by C. S. Bradley[85] early in 1893. The first shown by diagram (Fig. 57) consists of an alternating current motor having a primary element, two secondary elements, one of high resistance, the other of low resistance, and means for shifting the elements relatively so that the primary may cooperate with either or both secondary circuits. The last of these to be issued may be briefly described as a combined self-starting and synchronous alternating current motor provided with two windings, one comprising an element wound to develop a rotary magnetic field under differential phase currents cooperating with a closed circuit upon the other element; the other comprising a synchronous winding including a redirecting commutator, whereby the motor is rendered self-starting, and when it attains synchronous speed may be operated as a synchronous motor.

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[84] Spec. British Patent, 24,098, Aug. 26, 1893.

[85] Spec. U. S. Patents, 514,902, 514,903, 514,904, Feb. 20, 1894.

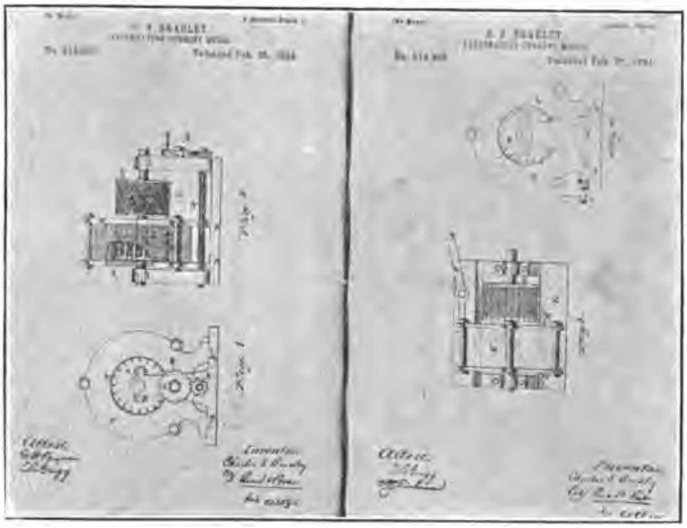

FIG. 57.

This was followed in June, 1893, by E. Thomson[86] who improved his apparatus considered previously (363,185 and 363,186) by making the number of inducing or field poles, and the number of armature coils subjected to induction, an odd one;

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[86] Spec. U. S. Patent, 516,849, March 20, 1894.

i. e., if there are two field poles then the armature has three coils, etc., the prime object being to secure smoothness of running. The coils are kept on closed circuits during normal running, either individually or collectively and the commutator is not used, the closure of the circuits being maintained throughout the revolution of the armature. Figure 58 shows a drawing of the improvement.

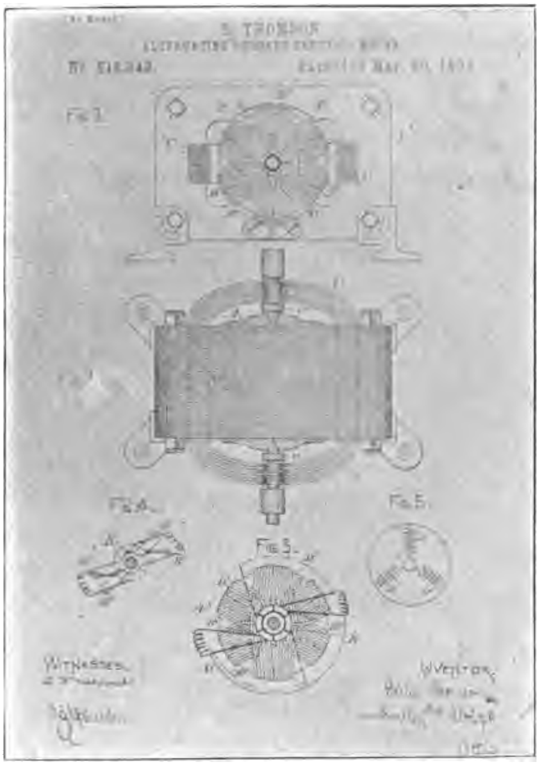

FIG. 58.

There are two important objections to the adaptation of direct current or commutator motors, to be used upon alternating current circuits,

1. Large no-load current and very low power factor, large air-gap necessary because of armature reaction, and large magnetic leakage; and,

2. Destructive sparking which occurs particularly at starting and on over load. This is due to heavy induced currents, which are set up in each coil as it is in turn short circuited by a brush, reacting upon the magnets and causing great heating and sparking.

Many attempts have been made to improve this form of motor, however, and one of the earlier methods was patented by Hutin and Leblanc[87] May 5, 1894. The application filed at the British patent office on June 20, 1893, is described according to specification as follows: "Our invention relates to the arrangement of commutators and brushes of electric machines which may be generators or motors, and to transformers particularly in cases where alternating currents are employed, in such a manner as to prevent short circuiting at the passing of brushes from one segment of the commutator to the next; and it relates also to the arrangement in electric machines and transformers of the magnetic field, and of the magnetic screen so as to utilize the forces for generating or moving more completely than in apparatus as they are usually constructed. In order to prevent sparking at the brushes, we add, above the ordinary plates of the brushes, a number of gauze plates insulated from each other by paper or the like and connect them through a graduated resistance to the body of the brushes so that as the brush leaves each segment these resistances are successively introduced before the circuit of the armature is entirely opened."

Another series of combinations for the prevention of the troublesome sparking at the commutator was patented by John Augustine Kingdon.[88] His arrangements, filed July 13, 1893, are best explained by the various claims set forth in his specification.

"1. An electro motor having more than one brush at each of its poles such brushes being insulated from one another, and connected with the supply mains through the split winding of the magnet coils."

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[87] Spec. British patent, 12,139, 1894.

[88] Spec. British Patent, 14,664, July 7, 1894.

"2. Splitting up the field magnet windings of an electric motor and utilizing the resistance of the split coils for checking the secondary currents induced in the armature coils under the brushes."

"3. Connecting the brushes of an electric motor with the split winding of an auxiliary transformer."

"4. An electric motor having groups of brushes insulated from one another at the brush holder, but connected through conducting coils wound on the motor or elsewhere."

"5. The combination in an electric motor of a commutator having insulating bars thicker than the brushes with two or more brushes at the poles insulated from one another and with split windings of the field magnet coils."

"6. Construction of an electric motor with primary and secondary coils on field magnets, the secondary being split up into two or more windings connected with the brushes."

"7. In an electric motor having two or more separate brushes at each pole insulated from one another, utilizing the resistance of conductors forming part of the winding of the motor or of apparatus connected therein to check secondary currents set up in the armature coils and prevent sparking." The latter device is indicated by the winding shown in Figure 59.

It is readily seen that up to this time (1893) the varieties of single-phase alternating current motors are summed up under the following heads:

1. Rotary field motors or those in which two or more energizing circuits furnish currents differing relatively in phase, cause a continuous progression of poles, and which thus produce the rotation of one member or element relatively to the other;

2. Magnetic lag motors, which have parts differing in magnetic susceptibility, so that the magnetic periods produced by the same current or different currents of the same phase, differ in the different poles;

3. Angular displacement motors, or those in which an energizing coil common to the field and to the armature is placed at

such an angle to the laminated field magnet, as to produce like poles in the respective parts in closer proximity to each other than the unlike poles, and so movement is produced by repulsion.

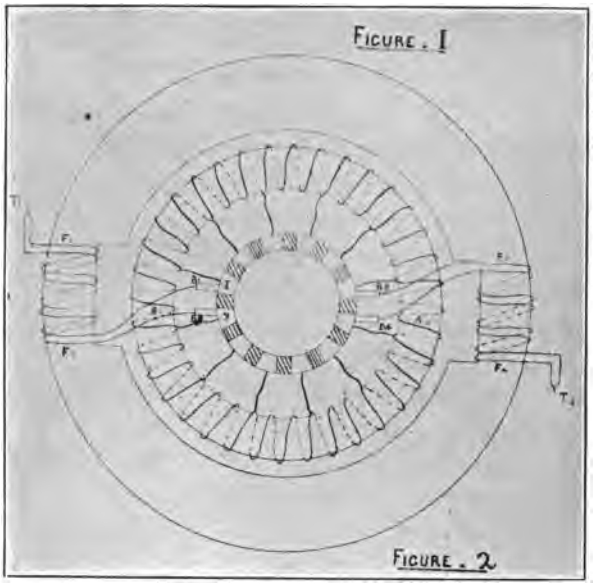

FIG. 59.

The alternating current motor of Joseph A. G. Trudeau[89] of Ottawa, Canada, the application for patent upon which was filed April 6, 1894, appears to be something of a departure from all of the above classes, as is indicated by Figure 60. This has independent and distinct fixed energizing coils which are employed for polarizing both the field and the armature, and both sets of coils receive current simultaneously and independently from the same generator, or from generators of like phase. The armature rotates within its own field energizing coils, so that while the points of maximum magnetic effect remain fixed in space the armature travels through the magnetic field. The claim is "in an electric motor, the combination with

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[89] Spec. U. S. Patent, 543,223, July 23, 1895.

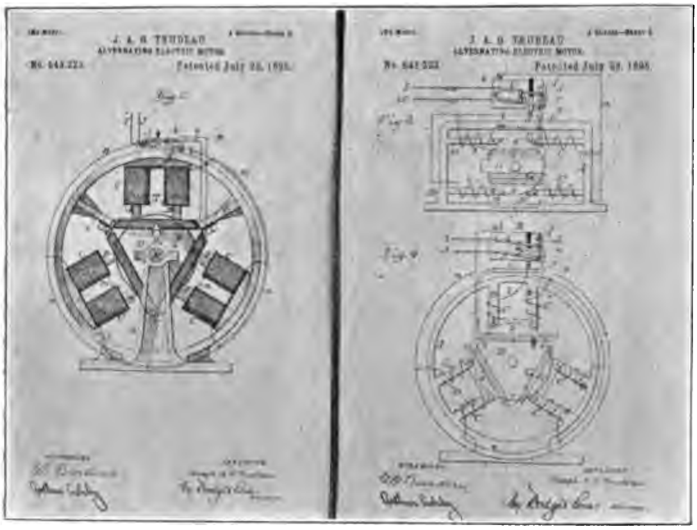

FIG. 60.

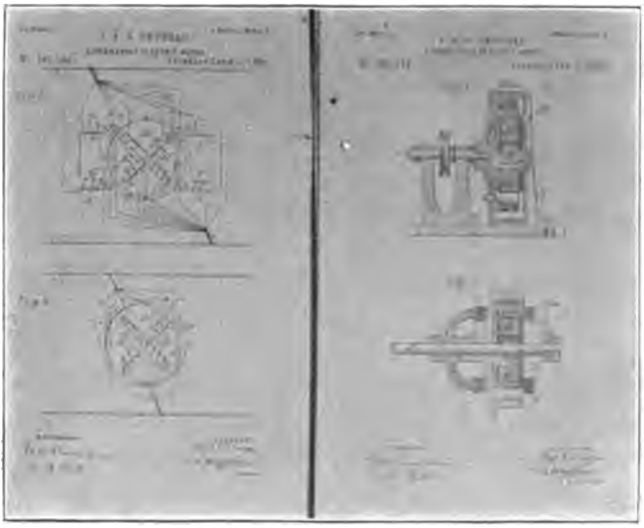

FIG. 61.

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suitable field magnets, of a rotatable armature having a circumferential iron hoop, and a non-magnetic central portion; an energizing coil encompassing the armature, and having its outer folds within the inner circumference of said hoop, whereby that portion of the hoop outside of the coil will be of one polarity through its entire thickness." This motor was improved upon later by its inventor in accordance with the diagram, Figure 61.[90]

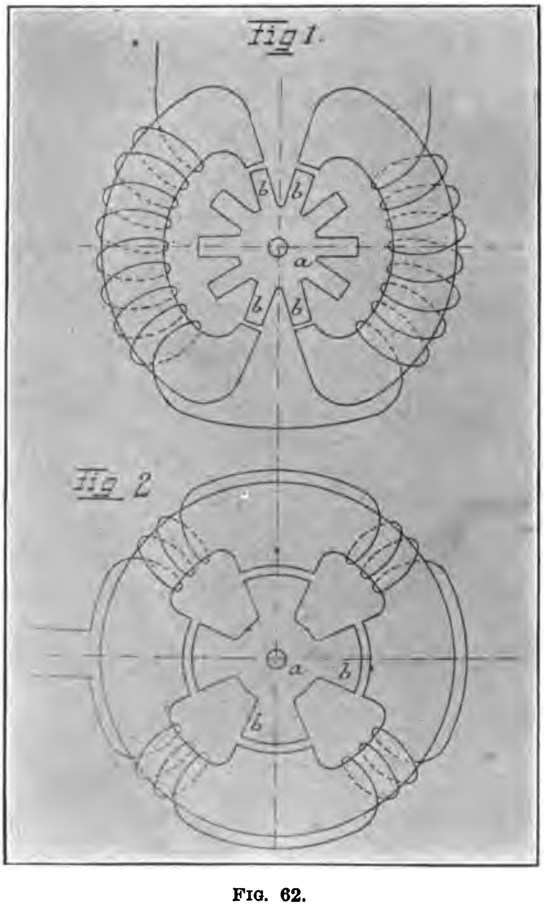

FIG. 62.

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[90] Spec. U. S. Patent, 561,144, 1896.

On April 11, 1894, Carl Coerper[91] of Germany, filed an application for a patent on a form of alternating current motor which is apparently more novel than practical; this arrangement consisted of a motor with a bare star shaped iron armature in which two neighboring arms of the star were subjected to the action of alternating magnetic poles. Fig. 62.

A little later, on May 16, 1894, a commutating alternating current motor was invented by William Morris Mordey,[92] who is so well recognized in connection with his work upon alternating current generators, which successfully eliminated much of the destructive sparking at the brushes.

This was followed by a novel method for reducing sparking, invented by Edward Andrews Clark[93] Oct. 23, 1894. This motor consisted of a field magnet with alternate and opposite poles; a closed circuit armature and its core with alternate and opposite poles; a commutator and its brushes short circuiting the armature coils; and masses of iron as J, J′, Figure 63, between the alternate and opposite poles of the field magnet, to reduce the current which is induced in the armature coils by the alternating current in the field coils.

Another arrangement by Brown, Walter Boveri, and Fritz Funk,[94] filed Jan. 1, 1895, combined with the motor a number of storage cells, and switching devices so as to include such cells in a portion of the inducing winding, to produce a rotary field. They serve by reason of capacity to prevent too great a fall of potential in the network of conductors on starting the motor. When the motor has attained its speed, the cells are switched out of the inducing coils, but may be left partly connected with the inducing coils if desired, in order to work the motor at a speed below normal.

Another form of split phase motor patented by Robert Lundell[95] is shown in diagram Figure 64. His application filed on Feb. 18, 1895, claims, "An alternating or pulsating current electric motor having an armature or rotary part provided with two sets of windings, one set being short circuited, and the other connected through a commutator to the secondary of a converter, the primary of which is connected directly to the current mains, the first magnet coils being also connected to the same mains through a variable resistance as shown."

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[91] Spec. British Patent, 7,239, June 9, 1894.
[92] Spec. British Patent, 9,605, April 27, 1895.
[93] Spec. British Patent, 20,241, Nov. 24, 1894.
[94] Spec. British Patent, 1,536, 1895.
[95] Spec. U. S. Patent, 560,591, May 19, 1896.

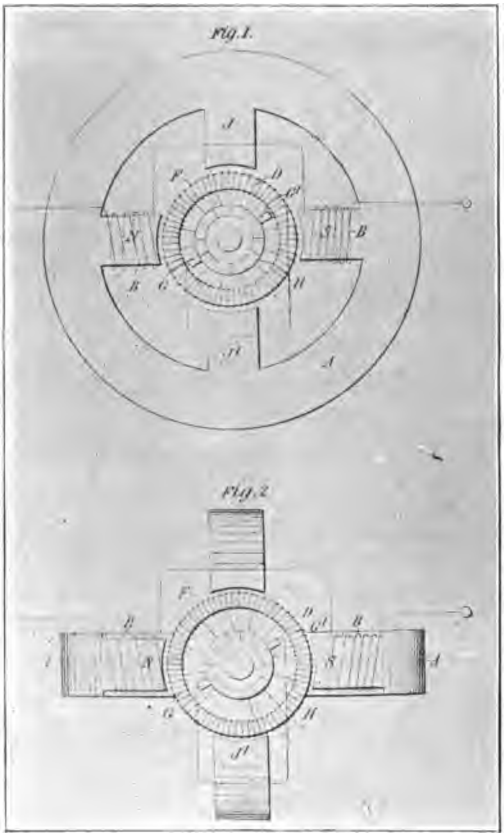

FIG. 63.

A phase splitting device operating on the general principle of the Wheatstone bridge is shown in Figure 65. This was filed on Jan. 30, 1897, by Siemens Bros.[96]

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[96] Spec. British Patent, 2,559, Dec. 11, 1897.

The English firm of Langdon-Davies Motor Co.[67] have in recent years become noted for the efficient type of single-phase motors manufactured by them. These self-starting motors, in fact, are now much used in Europe on single phase circuits.

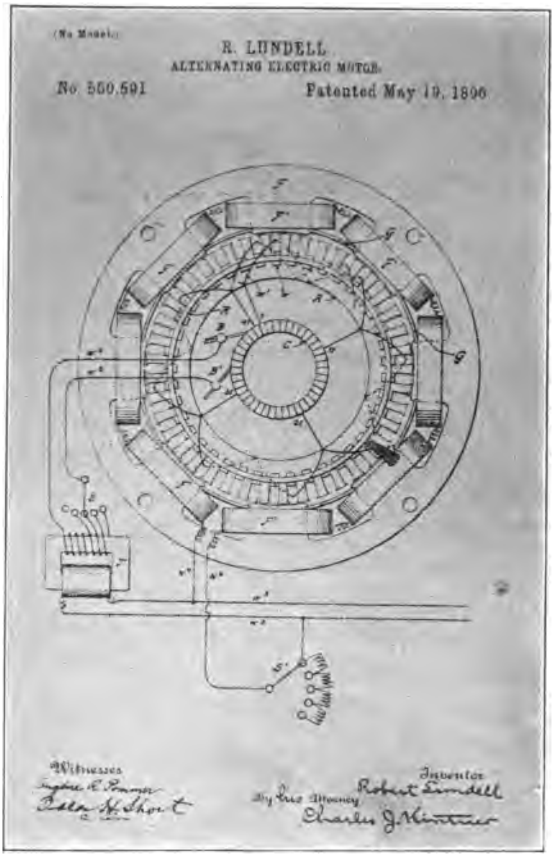

FIG. 64.

Mr. Walter Langdon-Davies has made exhaustive researches upon the arrangement of coils for producing a proper distribution of the magnetic field in single-phase motors, to give a uniform field and high efficiency, combined with a large starting

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[67] See London Electrician, June 19, 1896.
Engineering, June 19, 1896.

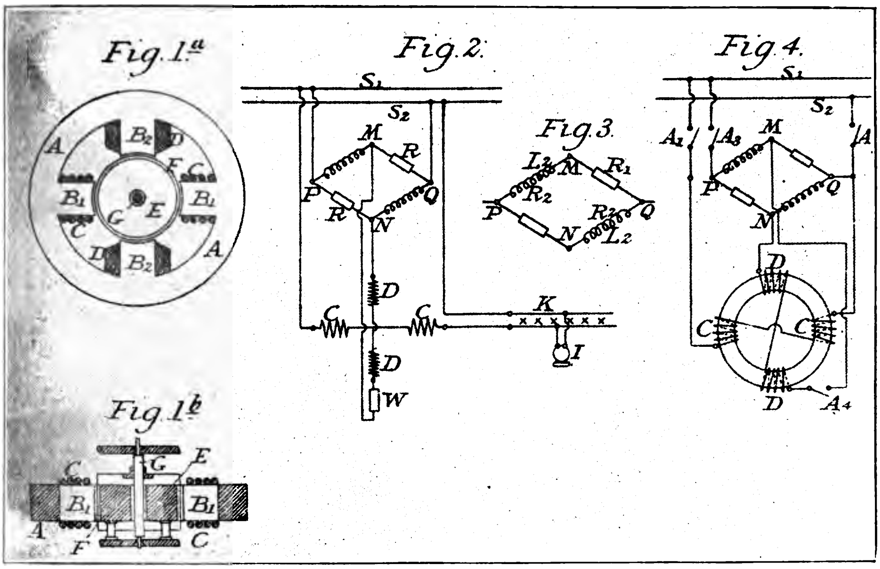
Fig. 1a
A
B2
D
F
C
B1
B1
G
E
C
D
B2
A
Fig. 1b
G
E
C
B1
B1
A
F
C
Fig. 2.
S1
S2
M
R
P
Q
R
N
D
C
C
K
D
I
W
Fig. 3.
L2
M
R1
P
R2
R2
Q
N
L2
Fig. 4.
S1
S2
A1
A3
M
A
P
Q
N
D
C
C
D
A4

FIG. 65.

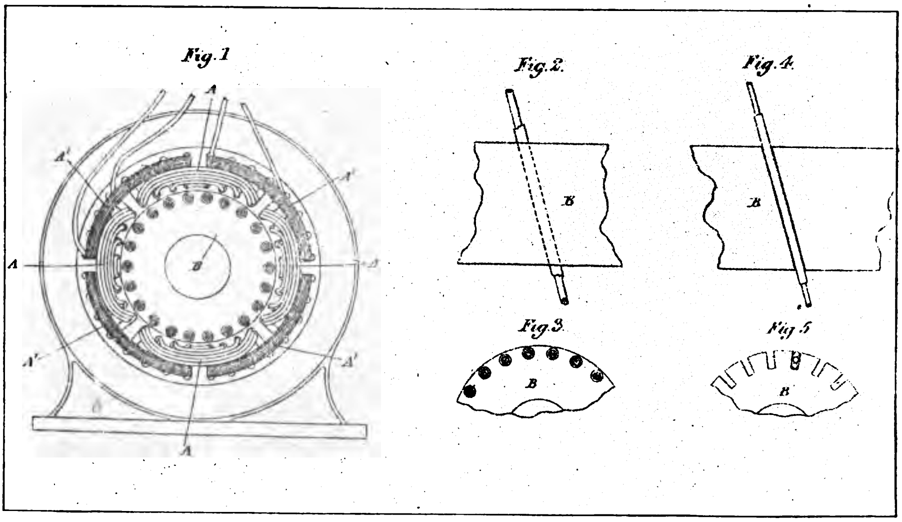
Fig. 1
A
A'
A'
A
A'
A'
A
B
Fig. 2.
B
Fig. 4.
B
Fig. 3.
B
Fig. 5
B

FIG. 66.

torque. Figure 67 shows a diagram of the winding of the field of a motor the application for patent upon which was filed by Langdon-Davies[98] on March 25, 1897. He claims for this,

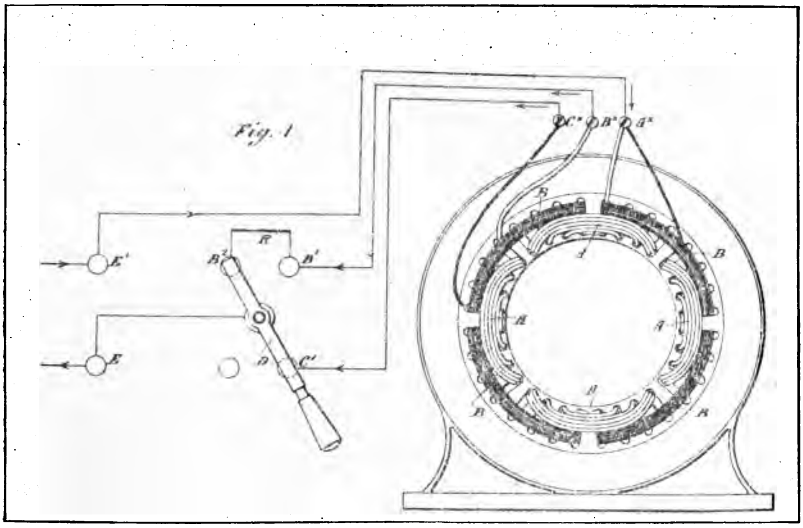

FIG. 67

"1. An alternating current motor in which the starting coils are of numerous turns and relatively high self-induction as compared with the running coils, and in which a resistance is added at starting to the circuit through the running coils.

"2. An alternating current motor in which the running coils have two or more wires which may be switched into series for starting and put in parallel when the motor has run up."

An improvement in this device was made by its inventor[99] July 7, 1897, is indicated in Figure 66, which had for its main feature the placing of either the field windings or the armature windings "askew" in order to produce a greater starting torque.

Elihu Thomson[100] describes a motor device invented August 19, 1897, briefly as follows:

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[98] Spec. British Patent, 7,772, Feb. 26, 1898.
[99] Spec. British Patent, 16,788, July 2, 1898.
[100] Spec. U. S. Patent, 664,190.

"The combination of a shaft or similar rotating body, means for connecting the shaft or body to some work consuming device, an alternating current induction motor of such design as to have a low starting torque, and higher running torque, a clutch for coupling the rotating member of the induction motor to said shaft or body, and automatic means for bringing the clutch into action when the torque of the motor is high and for causing the clutch to be out of operation or disengaged when the torque of the motor is low." Figure 68 represents a cross section of Thomson's device.

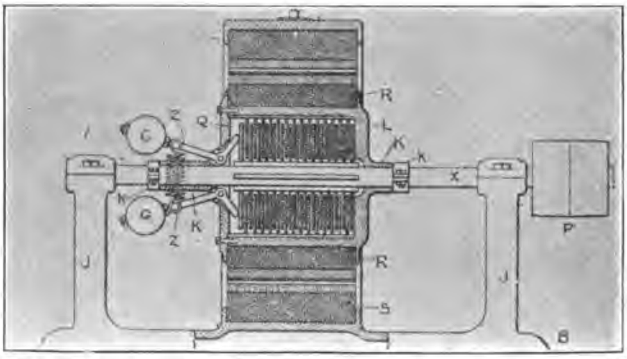

FIG. 68.

Anthony S. Frazer[1] of England took out patents in England, France, and the United States on a motor of which he says: "According to my invention I employ true single or monophase alternating currents, and the actual invention consists in the method employed to cause such currents to energize successively as magnetic poles certain equidistant points of a suitably wound laminated ring forming the rotor, and thereby to produce a uniformly rotary magnetic field the opposite active poles of which react on those of a bipolar ring stator which surrounds the rotor. To the spindle of the rotor is fixed a double crown wheel commutator, the projecting teeth of which are insulated from each other, forming a commutating or rectifying device over which is passed (directly that synchronous speed is attained) the impulses of an alternating current then made unindirectional for the purpose of energizing the coils of the stator, the poles of which then maintain between them a magnetic field of irregular intensity, but of constant direction. Impressed current is used for both the rotor and stator elements of the motor, and the arrangement of parts may be such as to take the current in series, or in parallel circuit relatively to each other." (Figure 69.)

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[1] Spec. U. S. Patent. 613,135, Oct. 25, 1898.

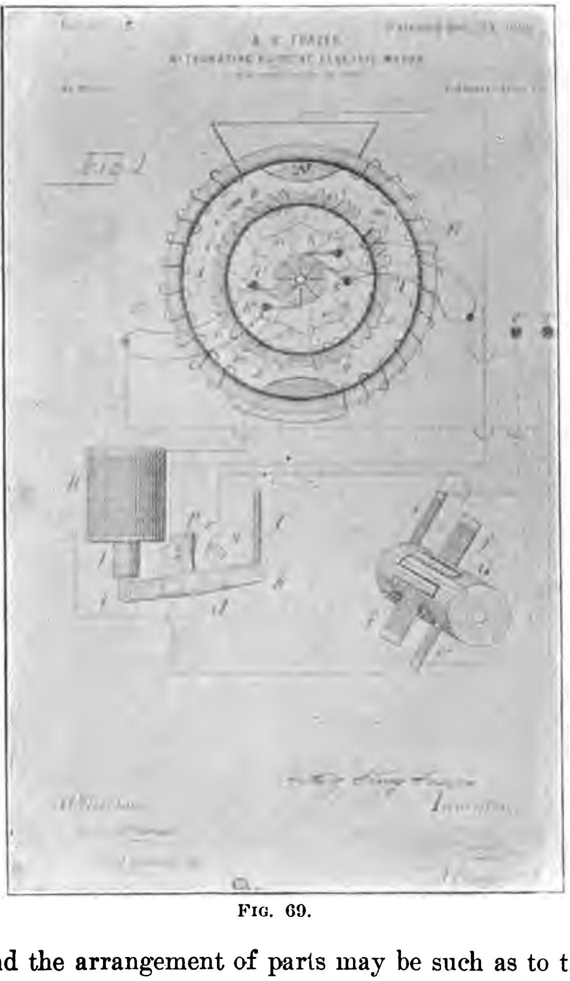

FIG. 69.

In concluding the consideration of patents issued on single phase motors and motor starting devices only those of Riccardo

Arno,[2] Turin; Thomas Duncan,[3] Fort Wayne; Conrad Rosenquist,[4] and The British Thomson Houston Company[5] will be mentioned.

Arno's method of starting monophase motors, Figure 70, is applied to motors with one set of windings only and is simple though scarcely applicable to the larger machines. It consists

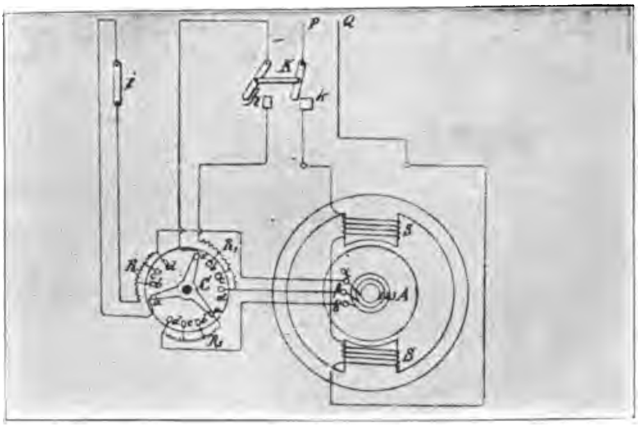

FIG. 70.

in inserting a suitable resistance in the rotor coils and momentarily rendering the coils of the rotor unsymmetrical and gradually cutting out this resistance as the motor comes to speed. His claim is in part: "A method of starting synchronous monophase alternating current motors, which consists in inserting in the rotor-coil circuits a resistance of r= .414x2 n L, *giving the motor a slight impulse,* and gradually cutting out the resistance."

Rosenquist's apparatus is understood by reference to the diagram (Fig. 71), and a brief consideration of his first claim which is: A single phase synchronous alternating current electric motor, whose main field magnet poles are slotted or perforated near the inner edge, and are supplied with two sets of windings, one winding surrounding the whole of each mainpolar projection, and the other winding surrounding one-half or a part of each of two adjacent main polar projections, combined with means whereby the latter winding is joined in series with the armature winding when the motor is started and replaced by the first mentioned winding when synchronism is attained.

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[2] Spec. U. S. Patent, 631,919.
[3] Spec. U. S. Patent, 623,528, April, 1899.
[4] Spec. U. S. Patent, 637,349.
[5] Spec. British Patent, 5,550, April, 1899.

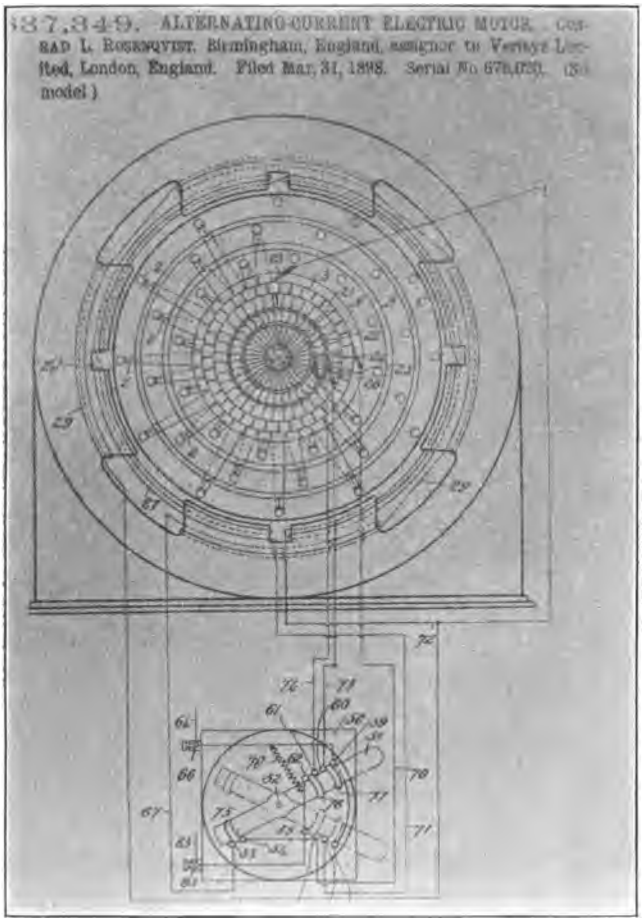
87,349. ALTERNATING-CURRENT ELECTRIC MOTOR. Conrad L. Rosenqvist, Birmingham, England, assignor to Veritys Limited, London, England. Filed Mar. 31, 1898. Serial No. 676,020. (No model.)

FIG. 71.

A general idea of the British T. H. Patent referred to, may be obtained by an inspection of Figure 72. This patent has to do with improvements in self-starting devices, by the introduction of certain combinations of inductance and condensance, or of resistance and reactance in parallel with the motor across the mains.

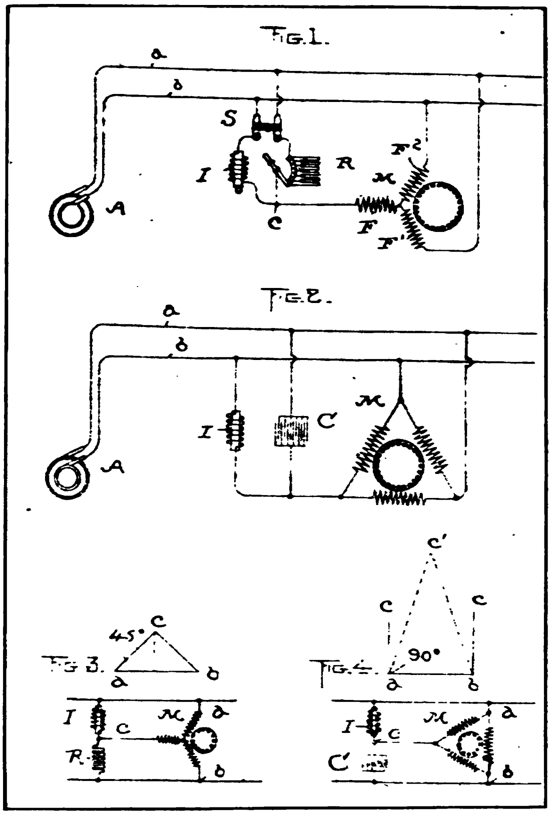

FIG. 72.

Alexander Heyland[6] has devised a form of single-phase self-starting motor. In this machine the chief winding is distributed in a set of slots, the leakage self-induction being reduced by having separate teeth over a considerable part of the periphery. The starting winding consists of closed coils wound in a bunched fashion so as to increase the leakage self-induction.

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[6] Elec. Eng., Sept., 1897.

A thin section of iron also bridges the slots holding these conductors. The currents induced in this closed winding, lag greatly and produce a cross field similar to another phase winding. His more recent work[7] on the polyphase motor may have also some bearing upon single-phase work.

Another interesting type of single-phase motor designed a short time ago by Prof. D. C. Jackson, consists of a rotor with two separate windings, one a commutated winding having resistance connectors joining successive segments of the commutator to avoid sparking, and the other, a winding short circuited through a variable resistance. In addition to being self-starting the motor possesses the advantage of practically sparkless running, together with the possibility of running above, below, or at synchronism, depending upon the resistance inserted in the short circuited winding. The latter feature is obviously useful in regulating the characteristics of the line current if it is desired.

It has been the aim of this paper thus far to present in chronological order the series of discoveries and inventions which have been of chief importance and significance in producing the present conditions relating to the transformation of energy by means of single-phase alternating current motors.

It must be understood that each and every one of the hundreds of men who have contributed a greater or less amount to the sum total of present knowledge on this subject, has not received attention herein. Indeed it would be next to impossible to enter into such detail with satisfaction either to the writer or to the reader. It is believed, however, that all the fundamental points and features have been covered so far as the representation of apparatus is concerned, and without entering into any theoretical discussion of the improvements or defects of such apparatus, it has seemed better to simply consider it briefly in order of development as far as it is known to the writer.

Such an elementary history of the subject, however, would scarcely be complete without a discussion of the modern theory of the action of single-phase motors and so that will next receive consideration.

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[7] Elektrotechn Zeitschr. Aug. 8, 1901.

Alternating current motors may be divided into two groups:

1. Motors with constant magnetic field.
2. Motors with alternating magnetic field.

The first group includes all those which are simple alternators used to deliver mechanical instead of electrical power. Such machines run synchronously when at speed, but ordinarily lack the important feature of being self-starting, and so necessitate an auxiliary mover to bring them to a point of usefulness. Some self-starting synchronous motors it is true have been constructed by Ferranti & Company, and by the Fort Wayne Company, the armature of the machine made by the latter being provided with both a commutator for starting and slip-rings for running.

While the disadvantage of synchronous motors, due to the lack of being self-starting may be overcome in various ways, they cannot be economically started under load, and while they are useful in long distance power transmission, for general power transmission and distribution they are quite unsatisfactory.[8]

"When a synchronous motor is put in circuit," says Jackson,[9] "a peculiar relation exists between the strength of the field motor and the current in its armature. In continuous-current motors, if the strength of the field is slightly changed without altering any of the other conditions, the speed of the motor changes inversely, and the current in the armature remains practically unchanged, but the speed of a synchronous motor cannot change permanently, and, consequently, upon first consideration, it would appear that the field of a synchronous motor must be exactly adjusted, in order that the machine may operate satisfactorily. This, however, is proven not to be the case in practice on account of the effect which may be gained through variations of the relative phases of the current and of the impressed and counter pressures. The active pressure, which at any instant causes current to flow through the armature of a motor, is equal to the difference of the corresponding instantaneous values of the impressed and counter pressures. If the field strength of the motor is so adjusted that the values of the impressed and counter pressures are equal, and the motor armature is brought into exact step with the impressed pressure curve, then, when the motor is switched on the supply main, it will fall back in phase with respect to the impressed pressure, sufficiently to permit the proper load current to pass through the armature. Now suppose that at some instant the load is increased, the difference of instantaeous pressures at that instant will be insufficient to pass the current, which is necessary for the new load, through the armature. The motor, therefore, falls back in its phase without losing synchronism, if the load is not too great, and then continues operating in synchronism, but with a greater lag in step. When a motor lags in step behind the phase of impressed electromotive force, its counter pressure lags to an equal extent. The armature current ordinarily takes an intermediate phase, so that it is behind the resultant pressure, but in advance of opposition to the counter pressure.

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[8] For literature on the theory of this type of motor see Picou, Transmission de Force par Moteurs alternatifs synchrones, Bull. Soc. Int. Electriciens, Vol. 12, p. 60; Blondel, Couplage et Synchronization des Alternateurs, La Lumière Electrique, Vol. 45, pp. 425, 563; Rhodes, A theory of synchronous motors, Phil. Mag., July, 1895; Alt. Current Motors, London Electrical Review, Vol. 37, pp. 182, 222.

Steinmetz, "Alternating Current Phenomena," p. 321.

Alternating Current Electric Motors, Dr. Louis Duncan, Elec. World, Vol. 17, pp. 341 and 357.

[9] "Alternating Currents and Alternating Current Machinery," D. C. and J. P. Jackson. Macmillan, 1898.

"Were it not for the effect of the current lag with respect to the resultant pressure, caused by self-inductance, it would be necessary to adjust the field excitation of a synchronous motor, so that its counter pressure would be less than the impressed pressure, and the range of load carried with a given excitation would be small. The effects due to the current lag, however, make it possible to adjust the field excitation once for all, so that the motor may be operated on a widely varying load. It is even possible, on account of the automatic adjustment of the pressure phases, to operate a motor when its excitation is much greater or much less than its normal value. The adjustment is assisted by the effect of armature reactions on the motor, in which a lagging current tends to strengthen the fields and a leading current to weaken them. When a single motor is operated from an alternator of about its own size the automatic adjustment of the machines is still more marked, since the current which strengthens the field of the motor tends to weaken that of the alternator as the load is varied, and vice versa, which is desired."

"It is evident from the preceding that the amature current of a motor must have a wattless component which depends directly upon the phase differences of the impressed and counter pressures and the angle of lag, and it may readily be seen that the most economical excitation of a synchronous motor field is that which reduces the armature current to a minimum (or makes the power factor a maximum), when the motor is carrying the average load."

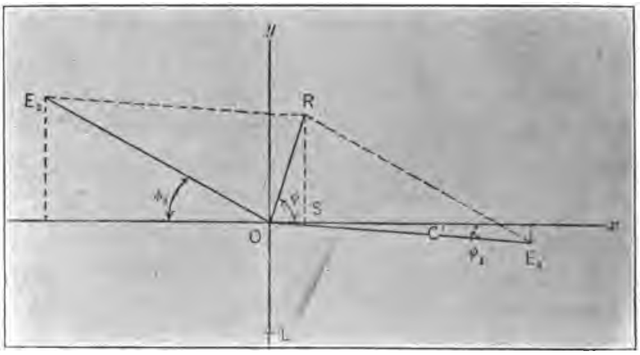

FIG. 73.

"In order to bring out more clearly the facts just given recourse may be had to a diagram in which relations of current and pressures are shown much as in parallel working. It was shown that in parallel working the machines were held in step by a motor action, and that if one machine was cut off from its prime mover it would continue to run in synchronism as a motor, its pressure being unchanged. In Figure 73 let OC be the current passing through two alternators, one acting as a motor, and let OL be the pressure of self-induction ($2 \pi f LC$), and OS the active pressure (CR); then OR will be the resultant pressure required to pass the current OC through the circuit. Suppose the alternator generates a pressure OE_1, and the motor is excited to give an equal pressure OE_2; then OE_1 and OE_2 must be in such a phase as to give the resultant OR, while the elements of pressure resolved upon the current line OC must be such that the element of OE_1 has the same direction as the current and the element of OE_2 is in opposition. The work delivered by the generator is $OC \times OE_1 \cos \phi_1$, and that utilized by the motor armature in furnishing power and overcoming the magnetic and friction losses is $OC \times OE_2 \cos \phi_2$; while that lost, due to resistance, is their difference, and is equal to $OC \times OR \cos \phi = OS \times OC$."

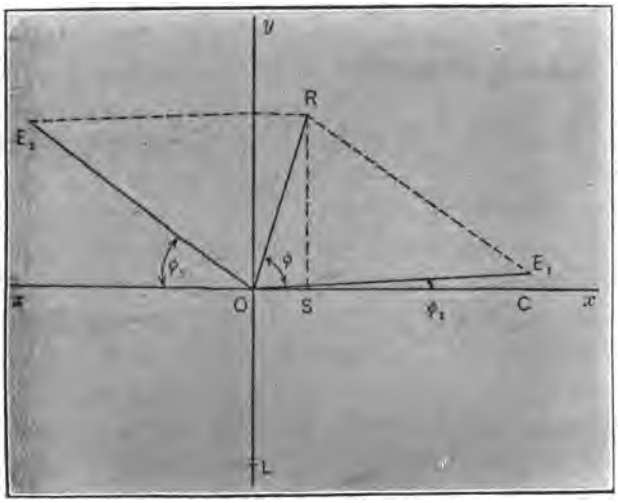

FIG. 74.

"It will be seen that for small loads the current may lead the generator pressure as shown in Fig. 73, but that as the load increases (and the length of OR therefore increases), the generator pressure is caused to swing forward so that the current takes a lagging position, as shown in Figure 74. The construction indicates that the current is always in the lead of direct opposition to the counter pressure when the impressed and counter pressures are equal, and the value of ϕ_2 increases when the load on the motor is increased. The value of C is one-half greater in Figure 74 than in Figure 73, the input of the motor is 50 per cent greater, and the output about 45 per cent greater. The latter is increased in a smaller proportion because the C^2R loss increases directly as C^2, while the output increases less rapidly than C. The motor will continue to operate, as the load is increased, until ϕ_2 has attained such a value that $E_2 \cos \phi \times C$ becomes a maximum; then, if an additional load is put on the motor, the corresponding increase of ϕ_2 will cause $CE_2 \cos \phi_2$ to decrease, and the motor will fall out of synchronism and stop, because the maximum value of its torque is not sufficient to pull the load. In the case under consideration (when the impressed and counter pressures are equal) this will not occur with well designed alternators until a load much above the normal is reached."

"The pressure at which the motor is run, and therefore its excitation, has an important bearing upon the stability of operation and the efficiency of transmission. If the motor pressure is made larger than that of the generator, the current and pressure relations may be shown by a construction similar to that used in Figure 73. Let OR in Figure 75 represent the magnitude and direction of the resultant pressure, and the impressed and counter pressures have magnitudes OE_1 and OE_2, then the parallelogram can be completed with but one value of the angles ϕ_1 and ϕ_2, i. e., that shown in the figure. In this case the counter pressure is greater than the impressed pressure. Now suppose the counter pressure is made OE'_2, having the same horizontal projection as OE_2, while OR and the impressed pressure have the same values as before; then the phase relations are as shown by the lines OR, OE'_1, and OE'_2. The values of $OE_2 \cos \phi_2$ and $OE'_2 \cos \phi'_2$ are equal by the construction, since the points E_2 and E'_2 are in the same vertical line, and since OR has the same magnitude and position in the two cases the current is the same, and $OE_1 \cos \phi_1$ and $OE'_1 \cos \phi^1_1$ are equal; but in the first place the counter pressure is greater than the impressed pressure and the current leads the impressed pressure and in the second case the impressed pressure is greater and the current lags. This construction shows that for every load on the motor, except that corresponding to a zero angle of the lag, there are two values of the excitation which cause the same armature current to flow, the current leading the impressed pressure with one excitation and lagging by an equal angle with the other excitation; hence an over excited motor acts upon the line current very much like a condenser, and an under-excited motor acts like an inductance coil. When the counter pressure is much less than the impressed pressure, the current may lag with respect to opposition to the counter pressure, but under no other conditions, and this is not a practical condition."

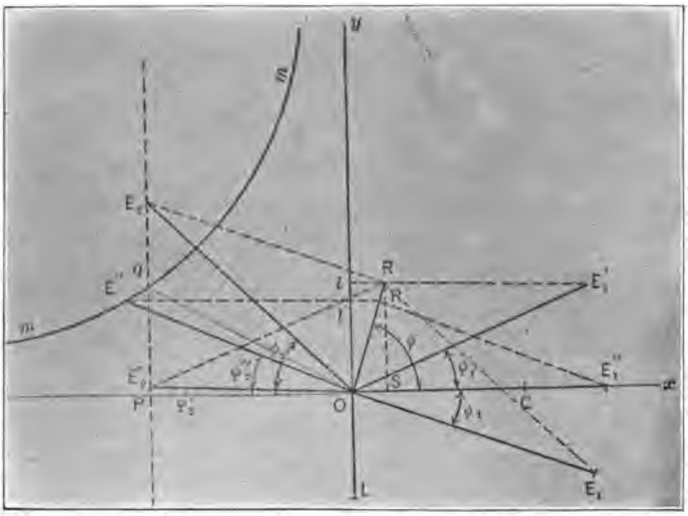

FIG. 75.

"The excitation at which the motor will do the most work with a given current flowing, or will carry a given load with the least current (and hence do it most efficiently), is that which causes the current to come into phase with the impressed pressure. In this case the current for a given load is a minimum, and $E_2 \cos \phi_2$ is a maximum. If the value of OE_2 in Figure 75 is increased (by increasing the excitation of the motor), either the length of OR which is proportional to C, or the impressed pressure, must be increased, provided $CE_2 \cos \phi_2$, which is equal to the motor load, is constant. On the other hand, if OE_2 decreases while OE_1 remains constant, the angle of lag, ϕ_1, and the current, decrease until the current and impressed pressure come into phase, after which a further decrease of OE_2 causes the current to increase again, as is shown by the relations between E_1, C, and E_2 in the figure. The value of $CE_2 \cos \phi_2$ is proportional to the area of the rectangle Olqp, since Ol is proportional to C. Now if the motor load is kept constant, but its excitation is changed, the corner of the corresponding rectangle must be different from q, but the locus of the motion of the corner is a hyperbola with its origin at O and the rectangular axes x and y, since the rectangles included between the axes and the ordinates and abscissas of all points must be of equal area. Consequently, the point of the vector representing E_2 at the least current for a given load must be in the rectangular hyperbola, mm, which passes through q. This point, which is E_2'' for the given load, is found by laying off the horizontal line equal in length to OE_1 which will just reach between the hyperbola and the line OR. This cuts OR at R′, and

$$C = \frac{E_l'' \ (=0l')}{2 \pi fL},$$

which is the minimum current for the load. The impressed pressure and current are, under these conditions, in phase with each other. At this point $E_2'' \sin \phi_2'' = E_b''$. If a larger or smaller pressure than OE''_2 is used, such as OE_2 or OE'_2, the impressed pressure and current are thrown out of phase, and the current in the circuit is therefore increased, which causes increased C^2R losses and armature reactions. The excitation of the motor which brings the current and impressed pressure into step depends upon the relation of the impedance of the motor circuit to its resistance. If I=2R, the counter pressure is equal to the impressed pressure at zero angle of lag, and if I $\gtrless$ 2 R, the counter pressure is respectively greater or less than the impressed pressure at zero lag. The expression I = 2 R is equivalent to, reactance equals $\sqrt{3}$ R (I $= \sqrt{R^2 + 4 \pi^2 f^2 L^2} = 2$ R, and therefore $2 \pi f L = \sqrt{3}$ R). In the machines which are now commonly built, the impedance of the armature circuit is commonly equal to or larger than twice the resistance, so that a maximum power factor is gained in such synchronous motors by an excitation which gives a counter pressure that is equal to or greater than the impressed pressure."

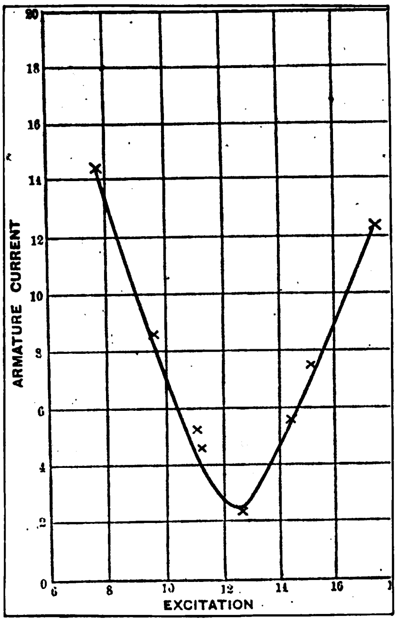

FIG. 76.

"We may plot the relation of armature current to field excitation for a motor operating under the conditions considered above, by taking the corresponding values of E_2 and C from a chart made like Fig. 75. This gives a curve like Figure 76, which has two values of its abscissas for every value of the ordinate except the lowest; or for each value of the armature current there may be two values of the excitation, one being greater and the other less than the impressed pressure, except at the point of minimum armature current, which corresponds to but one excitation, as has already been explained. The way in which Figure 75 is constructed shows that the smaller angle ϕ, or the smaller the armature self-inductance, the less will be the difference in the two excitations corresponding to any armature current; and hence the curve showing the relation of excitation to current in a machine having a large time constant is broad and rounded, but the curve for the armature having a small time constant is sharp and narrow. In an ideal machine without self-inductance, the two values of excitation for a leading and lagging impressed pressure are equal, and the curve becomes a straight line."

"When a synchronous motor is operated with a fixed excitation on a variable load, the step of the motor will automatically adjust itself, when the load changes, to the changed conditions, until $CE_2 \cos \phi_2$ is equal to the new load, provided a certain maximum limit is not exceeded. As the load increases the current must increase, whence it is evident from Figure 75 that the change in phase of the motor pressure must be in the direction which increases ϕ_2, and that $CE_2 \cos \phi_2$ will therefore reach a maximum point beyond which the motor cannot work, since $\cos \phi_2$ decreases as ϕ_2 increases. This point depends upon the self-inductance of the armature, which controls ϕ_2, when the impressed and counter pressures are constant. If the load on the motor is made greater than the maximum value of $CE_2 \cos \phi_2$, the motor must fall out of synchronism and stop. The smaller the impedance of the motor circuit, the less will the angle ϕ_2 change with any change of current, when E_2 remains constant, as is seen by the construction of Figure 15, and therefore the maximum load which the motor will carry depends inversely on its impedance; but the greater the angle of lag, ϕ, the less will be the value of ϕ'_2 for fixed values of the pressures and impedance, and consequently the less rapidly will cos ϕ_2 vary with a given variation of ϕ_2. So that the maximum load which a motor will carry depends inversely upon the impedance of its armature circuit, and directly upon the angle by which the current lags behind the resultant pressure. In practice, armature reactions always tend to weaken the field of the motor as the current is in the lead of opposition to the counter pressure; and it is therefore advisable to excite the machine rather above that pressure corresponding to the least current for normal load, as the armature reactions then tend to decrease the field strength and thus modify the motor pressure so as to cause a decrease in the amount of armature current. If the excitation is made smaller than that corresponding to minimum current, the armature reactions cause the deviation from minimum current to become still greater. To decrease the effect of armature reactions as well as make the machine capable of carrying considerable overloads without being dragged out of synchronism, it is advisable to use strong fields, and armatures with the least number of conductors compatible with an economical design. There is ordinarily no danger to the motor if it stops, as the armature inductance cannot be economically reduced below a value sufficient to prevent a destructive flow of current."

Another graphical method of treatment which has some advantage is as follows:[10] "Let OA (Fig. 77) represent the electromotive force applied at the terminals of the motor; if E_a is its maximum value then

$$E_a = m\,O\,A$$

If O B represents the counter electromotive force of the motor making with the applied E.M.F. the angle ψ then

$$E_c = m\,O\,B.$$

If we take $O\,B' = O\,B$, $B'\,A$ represents in magnitude and direction the resultant, and we have

$$E_r = m\,B'\,A$$

If L is the coefficient of self-induction of the motor, r the resistance of the armature, and if $\tan \phi = \frac{kL}{r}$, in taking the angle B′ A C $= \phi$, and by dropping from B′ the perpendicular B′ C on A C we have:

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[10] "Courants Alternatifs Industriels" Loppé et Bouquet, Paris, 1896.

$$E_s = m\,B'\,C$$

E_s being the maximum value of the E.M.F. of self-induction C A represents the E.M.F. which is in phase with the current.

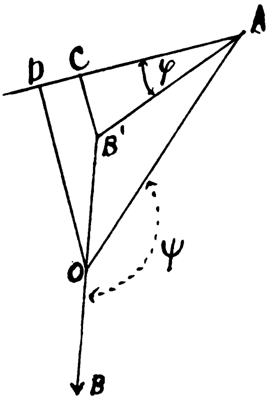

FIG. 77.

If I is the maximum intensity of the current we have:

$$I = \frac{E_a}{r} = \frac{m\ C\ A}{r}$$

The power furnished to the motor is:

$$P_a = E_{a\ eff}\, I_{eff} \cos D\ A\ O =$$

$$\frac{E_a\, I}{2} \cos D\ A\ O$$

In dropping from O, the perpendicular O D on C A, we have:

$$\cos D\ A\ O = \frac{D\ A}{O\ A} \qquad E_a = m\ O\ A \qquad I = \frac{m}{r}\ C\ A.$$

$$P_a = \frac{m^2}{2r}\ O\ A.\ \ C\ A.\ \ \frac{D\ A}{O\ A} = \frac{m_2}{2r}\ D\ A.\ \ C\ A.$$

The power lost or transformed into heat is:

$$P_p = r\,I^2_{eff} = r\,\frac{I^2}{2} = \frac{m^2\,r}{2r^2}\,\overline{C\,A}^2 = \frac{m^2}{2\,r}\,\overline{C\,A}^2$$

The useful power is:

$$P_a = E_{c\;eff}\,I_{eff}\cos\,(CA,\,OB)$$

As O D is perpendicular to C A, we have

$$\cos\,(CA,\,OB) = \sin\,B'\,O\,D = \frac{DC}{O\,B'}$$

$$E_{c\;eff} = \frac{E_c}{\sqrt{2}} = m\,\frac{O\,B}{\sqrt{2}}$$

$$I_{eff} = \frac{I}{\sqrt{2}} = \frac{m}{r}\,\frac{C\,A}{\sqrt{2}}$$

$$P_u = \frac{m^2}{2r}\,O\,B.\quad C\,A\,\frac{D\;C}{O\;B} = \frac{m^2}{2r}\,DC.\quad CA.$$

It is easy to verify the equation:

$$P_u = P_a - P_p = \frac{m^2}{2r}\,(DA.\quad CA - CA^2)$$

$$P_u = \frac{m^2}{2r}\,(DA - CA)\,CA = \frac{m^2}{2r}\,DC.\quad CA.$$

Therefore:

1. The power furnished to the motor is proportional to:

$$DA.\quad CA$$

2. The power lost, to:

$$\overline{CA}^2$$

3. The useful power, to:

$$DC.\quad CA.$$

The efficiency will be

$$\frac{DC.\;\;CA}{DA.\;\;CA} = \frac{DC''}{DA.}$$

The second group of motors includes two principal types:

I. Commutator motors, which may be divided into:
   a. Repulsion motors,
   b. Series motors,
   c. Shunt motors, and
II. Induction motors.

Commutator motors have been built of the various kinds enumerated above, prominent examples of which have been illustrated. These motors even at the best, however, have not been extensively used because of the superiority of induction and synchronous motors.

a. The repulsion motor is a transformer motor essentially, wherein the main current enters the field circuit only, while a current is induced in the armature so that the effect produced is the result of a repulsive thrust between induced current and inducing magnetism. Now if the armature circuits are all kept constantly closed, the primary circuits will not cause the armature to rotate because in half of the armature coils the current induced tends to produce rotation in one direction, while in the other half the current induced tends to produce rotation in the opposite direction. This means that a commutator must be introduced in order to short-circuit successively the coils that will give a rotary effort in the desired direction. Brushes are arranged to short-circuit a part of the armature coils; or, the whole armature may be short-circuited by a connection from brush to brush. The first arrangement is open to the objection of using only a part of the armature coils at any given time; while the latter has the disadvantage that, as the brush passes from segment to segment of the commutator, individual armature coils are short circuited and so a torque is produced in opposition to that of the main induced current flowing through the whole armature from one brush to the other. The repulsion motor therefore includes a primary field circuit, a magnetic circuit, and a secondary circuit closed upon itself and displaced by perhaps 45 degrees—in a bipolar motor—from the direction of magnetic flux. The secondary circuit, though moving, retains its 45 degree position virtually, since the secondary circuits are continually replacing one another. If we consider E.M.F., current, resistance, reactance, etc., reduced to the primary circuit by the ratio of turns then, according to Steinmetz, let

"ϕ = maximum magnetic flux per field pole;
e = effective E.M.F. induced thereby in the field turns; then
$e = \sqrt{2}\,\pi\, N\, n\, \phi\, 10^{-8}$;
where n = numbers of turns, N = frequency.

And
$$\phi = \frac{e\, 10^8}{\sqrt{2}\,\pi\, n\, N}$$

The instantaneous value of magnetism is
$$\phi = \phi \sin \beta;$$

and the flux interlinked with the armature circuit
$$\phi_1 = \phi \sin \beta \sin \lambda;$$

when λ is the angle between the plane of the armature coil and the direction of the magnetic flux. (Usually about 45 degrees.) The E.M.F. induced in the armature circuit, of n turns (as reduced to primary circuit), is thus,

$$e_1 = -\, n \frac{d\,\phi_1}{d\,t} 10^{-8}, = -\, n\, \phi \frac{d}{d\,t} \sin \beta \sin \lambda\, 10^{-8},$$

$$= -\, n\, \phi \left\{ \sin \lambda \cos \beta \frac{d\,\beta}{d\,t} + \sin \beta \cos \lambda \frac{d\,\lambda}{d\,t} \right\} 10^{-8}.$$

If N = frequency in cycles per second, N_1 = frequency of rotation or speed in cycles per second, and $k = N_1/N =$
$$\frac{\text{speed}}{\text{frequency}}$$

we have
$$\frac{d\,\beta}{d\,t} = 2\,\pi\, N;\ \frac{d\,\lambda}{d\,t} = 2\,\pi\, N_1 = 2\,\pi\, k\, N;$$

thus
$$e_1 = -\, 2\,\pi\, n\, N\, \phi\, (\sin \lambda \cos \beta + k \cos \lambda \sin \beta)\, 10^{-8}.$$

or, since
$$\phi = \frac{e\, 10^8}{\sqrt{2}\,\pi\, n\, N},$$

$$e_1 = e \sqrt{2}\, (\sin \lambda \cos \beta + k \cos \lambda \sin \beta),$$

"Introducing now complex quantities, and counting the time from the zero value of rising magnetism, the magnetism is represented by $j\,\phi$,
the primary induced E.M.F., $\underset{\cdot}{E} = -e$,

the secondary induced E.M.F., $\underset{\cdot}{E_1} = -e\,(\sin\lambda + jk\cos\lambda)$;
hence, if

$Z_1 = r_1 - jx_1$ = secondary impedance reduced to primary circuit,
$Z = r - jx$ = primary impedance,
$Y = g - jb$ = exciting admittance,

we have,

secondary current,

$$\underset{\cdot}{I_1} = \frac{\underset{\cdot}{E_1}}{Z_1} = -e\,\frac{\sin\lambda + jk\cos\lambda}{r_1 - jx_1}$$

primary exciting current,

$$\underset{\cdot}{I_0} = e\,Y = e\,(g + jb),$$

hence, total primary current,

$$\underset{\cdot}{I} = \underset{\cdot}{I_0} - \underset{\cdot}{I_1} = e\,(g + jb + e\,\frac{\sin\lambda + jk\cos\lambda}{r_1 - jx_1}$$

Primary impressed E.M.F.,

$$\underset{\cdot}{E_0} = -\underset{\cdot}{E} + \underset{\cdot}{I}Z;$$

$$= e\left\{1 + (\sin\lambda + jk\cos\lambda)\,\frac{r - jx}{r_1 - jx_1} + (g + jb)\,(r - jx)\right\}$$

Neglecting in E_0 the last term, as of higher order,

$$\underset{\cdot}{E_0} = e\left\{1 + \sin\lambda + jk\cos\lambda\,\frac{r - jx\,;}{r_1 - jx_1}\right\}$$

or, eliminating imaginary quantities,

$$e_0 = \frac{e\sqrt{(r_1 + r\sin\lambda + kx\cos\lambda)^2 + (x_1 + x\sin\lambda - kr\cos\lambda)^2}}{\sqrt{(r_1^2 + x_1^2)}}$$

The power consumed by the component of primary counter E.M.F., whose flux is interlinked with the secondary e sin λ, is,

$$P' = (e \sin \lambda \underset{\cdot}{I})' = \frac{e^2 \sin \lambda \, (r_1 \sin \lambda - k x_1 \cos \lambda)}{r_1^2 + x_1^2},$$

the power consumed by the secondary resistance is,

$$P_1 = I_1^2 \, r_1 = \frac{e^2 \, r_1 \, (\sin^2 \lambda + k^2 \cos^2 \lambda)}{r_1^2 + x_1^2}$$

hence the difference, or the mechanical power developed by the motor armature,

$$P = -\,(P' - P_1) = \frac{e^2 \, k \cos \lambda}{r_1^2 + x_1^2} \, (x_1 \sin \lambda + r_1 \, k \cos \lambda),$$

and substituting for e,

$$P = \frac{e_o^2 \, k \cos \lambda \, (\, x_1 \sin \lambda + r_1 \, k \cos \lambda)}{(r_1 + r \sin \lambda + kx \cos \lambda)^2 + (x_1 + x \sin \lambda - kr \cos \lambda)^2}$$

and the torque in synchronous watts,

$$T = \frac{P}{k} = \frac{e_o^2 \cos \lambda \, (x_1 \sin \lambda + r_1 \, k \cos \lambda)}{(r_1 + r \sin \lambda + kx \cos \lambda)^2 + (x_1 + x \sin \lambda - kr \cos \lambda)^2}$$

Or

$$T = \sqrt{2}\, \pi \, N \, 10^{-8} \, (j_1 \, \phi \sin \lambda \, \underset{\cdot}{I_1} \cos \lambda)' = (e_1 \, \underset{\cdot}{I_1} \cos \lambda) j$$

$$= \frac{e^2 \cos \lambda \, (x_1 \sin \lambda + r_1 \, k \cos \lambda)}{r_1^2 + x_1^2} \text{ etc.}$$

The stationary torque is, k = O,

$$T_o = \frac{e_o^2 \, x_1 \sin \lambda \cos \lambda}{(r_1 + r \sin \lambda)^2 + (x_1 + x \sin \lambda)^2},$$

and neglecting the primary impedance, r = O = x,

$$T_o = \frac{e_o^2 \, x_1 \sin \lambda \cos \lambda}{r_1^2 + x_1^2} = \frac{e_o^2 \, x_1 \sin^2 \lambda}{2 \, (r_1^2 + x_1^2)}$$

which is a maximum at λ = 45 degrees.

At speed k, neglecting $r = 0 = x$,

$$T = \frac{e_0^2 \cos \lambda \,(x_1 \sin \lambda + r_1 k \cos \lambda)}{r_1^2 + x_1^2},$$

which is a maximum for $\frac{dT}{d\lambda} = 0$, which gives,

$\cot 2\lambda = \frac{r_1 k}{x_1}$. For $k = 0$, $\lambda = 45$ degrees; for $k = \infty, \lambda = 0$. That is, in the repulsion motor, with increasing speed, the angle of secondary closed circuit, λ, has to be reduced to get maximum torque.

At $\lambda = 45$ degrees we have,

$$T = \frac{e_0^2 \,(x_1 + r_1 k)}{(r_1 \sqrt{2} + r + kx)^2 + (x_1 \sqrt{2} + x - kr)^2}$$

and the power,

$$P = \frac{e_0^2 k \,(x_1 + r_1 k)}{(r_1 \sqrt{2} + r + kx)^2 + (x_1 \sqrt{2} + x - kr)^2}$$

this is a maximum, at constant $\quad = 45$ degrees,

$$\text{for } \frac{dP}{dk} = 0,$$

which gives,

$$k = \frac{x + x_1 \sqrt{2}}{x},$$

At $\lambda = 0$ we have,

$$T = \frac{e_0^2 r_1 k}{(r_1 + kx)^2 + (x_1 - kr)^2},$$

That is, $T = 0$ at $k = 0$, or, the motor is not self-starting, when $\quad = 0$.

$$P = \frac{e_0 r_1 k^2}{(r_1 + kx)^2 + (x_1 - kr)^2},$$

which is a maximum at constant

$$\lambda = 0 \text{ for, } \frac{dP}{dk} = 0,$$

which gives,

$$k = \frac{r_1^2 + x_1^2}{rx_1 - xr_1}.$$

b. Similarly in a series motor let,

"ϕ = effective magnetism per pole,
n = number of field turns per pole in series,
n_1 = number of armature turns in series between brushes,
P = number of poles,
R = magnetic reluctance of field circuit,
R_1 = magnetic reluctance of armature circuit,
ϕ_1 = effective magnetic flux produced by armature current (cross magnetization) per pole,
r = resistance of field (effective resistance, including hysteresis),
r_1 = resistance of armature (effective resistance, including hysteresis),
N = frequency of alternations,
N_1 = speed in cycles per second.

It is then,

E.M.F. induced in armature conductors by their rotation through the magnetic field (counter E.M.F. of motor).

$$E = 4\ n_1\ N_1\ \phi\ 10^{-8},$$

E.M.F. of self-induction of field,

$$E' = 2\ \pi\ p\ n\ N\ \phi\ 10^{-8},$$

E.M.F. of self-induction of armature,

$$E_1' = 2\ \pi\ n_1\ N\ \phi_1\ 10^{-8}.$$

E.M.F. consumed by resistance,

$$E_r = (r + r_1)\ I.$$

where,

I = current passing through motor, in amperes effective.

Further, it is:

Field magnetism:

$$\phi = \frac{n\ I\ 10^8}{R}$$

Armature magnetism:

$$\phi = \frac{n_1 \; I \; 10^8}{R_1}.$$

Substituting these values,

$$E = \frac{4 \; n n_1 \; N_1 \; I}{R};$$

$$E' = \frac{2 \; \pi \; p n^2 \; N I}{R};$$

$$E_1' = \frac{2 \; \pi \; n_1^2 \; N I}{R_1}$$

$$E_r = (r + r_1) \; I.$$

Thus the impressed E.M.F.,

$$E_o = \sqrt{(E + E_r)^2 + (E' + E_1')^2}$$

$$= I \sqrt{\left(\frac{4 \; n n_1 \; N_1}{R} + r + r_1\right)^2 + 4 \; \pi^2 \; N^2 \left(\frac{p n^2}{R} + \frac{n_1^2}{R_1}\right)^2};$$

or, since

$$x = 2 \; \pi \; N \frac{p n^2}{R} = \text{reactance of field;}$$

$$x_1 = 2 \; \pi \; N \frac{n_1^2}{R_1} = \text{reactance of armature;}$$

$$E_o = I \sqrt{\left(\frac{4 n n_1 \; N_1}{R} + r + r_1\right)^2 + (x + x_1)^2}$$

$$= I \sqrt{\left(\frac{2}{\pi} \frac{n_1}{p n} \cdot \frac{N_1}{N} \; x + r + r_1\right)^2 + (x + x_1)^2};$$

and

$$I = \frac{E_0}{\sqrt{\left(\frac{4nn_1\,N_1}{R} + r + r^1\right)^2 + 4\,\pi^2\,N^2\left(\frac{pn^2}{R} + \frac{n_1^2}{R_1}\right)^2}}$$

$$= \frac{E_0}{\sqrt{\left(\frac{4nn_1\,N_1}{R} + r + r_1\right)^2 + (x + x_1)^2}}$$

$$= \frac{E_0}{\sqrt{\left(\frac{2}{\pi}\,\frac{n_1}{pn}\,\frac{N_1}{N}\,x + r + r_1\right)^2 + (x + x_1)^2}}$$

The power output at armature shaft is,

$P = E\,I$

$$= \frac{\frac{4nn_1\,N_1}{R}E_0^2}{\left(\frac{4nn_1\,N_1}{R} + r + r_1\right)^2 + 4\,\pi^2\,N^2\left(\frac{pn^2}{R} + \frac{n_1^2}{R_1}\right)^2}$$

$$= \frac{\frac{4\,nn_1\,N_1}{R}\,E_0^2}{\left(\frac{4\,nn_1\,N_1}{R} + r + r_1\right)^2 + (x + x_1)^2}$$

$$= \frac{\frac{2}{\pi}\,\frac{n_1}{pn}\,\frac{N_1}{N}\,x\,E_0^2}{\left(\frac{2}{\pi}\,\frac{n_1}{pn}\,\frac{N_1}{N}\,x + r + r_1\right)^2 + (x + x_1)^2}$$

The displacement of phase between current and E.M.F. is

$$\tan\bar{\omega} = \frac{E' + E_1'}{E + E_r}$$

$$= \frac{2\,\pi\,N\left(\frac{pn^2}{R} + \frac{n_1^2}{R_1}\right)}{\frac{4nn_1\,N_1}{R} + r + r_1}$$

$$= \frac{x + x_1}{\frac{2}{\pi}\,\frac{n_1}{pn}\,\frac{N_1}{N}\,x + r + r_1}.$$

Neglecting, as approximation, the resistance $r + r_1$, it is,

$$\tan\hat{\omega} = \frac{1 + \frac{x_1}{x}}{\frac{2}{\pi}\frac{n_1}{pn}\frac{N_1}{N}}$$

$$P = \frac{E_o^2}{\frac{2}{\pi}\frac{n_1}{pn}\frac{N_1}{N} + \frac{\left(1 + \frac{x_1}{x}\right)^2}{\left(\frac{2}{\pi}\frac{n_1}{pn}\frac{N_1}{N}\right)}}$$

hence a maximum for,

$$\frac{2}{\pi}\frac{n_1}{pn}\frac{N_1}{N} = \frac{\left(1 + \frac{x_1}{x}\right)^2}{\left(\frac{2}{\pi}\frac{n_1}{pn}\frac{N_1}{N}\right)}$$

or,

$$\frac{N_1}{N} = \frac{1 + \frac{x_1}{x}}{\frac{2}{\pi}\frac{n_1}{pn}}$$

Substituting this is $\tan\hat{\omega}$, it is:

$\tan\hat{\omega} = 1$, or, $\hat{\omega} = 45$ degrees."

c. A shunt motor having a laminated field will possess a good starting torque, since at starting both field and armature currents are greatly lagging and so approximately in phase. Under running conditions, however, this motor is very unsatisfactory because with increasing speed the armature current does not tend to come into phase with the impressed E.M.F. as it should do to represent power.

In order to operate a motor of this type, the magnetism of the field should be approximately in phase with the impressed E.M.F., and in order to meet this condition, capacity is inserted in the field circuit, and under such conditions the theory of the series motor holds also for the shunt motor. There is evidently much difficulty in keeping the balance that is necessary between capacity and self-induction in the field circuit, on account of slight variations in frequency, and so these motors are of little practical value.

The great objection to both series and shunt motors, however, is the vicious sparking at the commutator, as has been indicated on a previous page. This is explained by noting that when the brushes are normally mid-way between the field-poles, the armature coil passing under a brush encloses the total magnetic flux. At this instant, therefore, no E.M.F. is induced in the coil due to its rotation, but the E.M.F. induced by the alternations of magnetic flux is at its maximum value, and thus the coil acts as a short circuited secondary to the field current as primary, and so an excessive amount of current tends to flow through the armature coil, and is interrupted by the motion of the armature, with the resulting destructive spark.

Various arrangements have been devised to allay this difficulty of which one of the most promising consists in connecting segment to segment all the way around the commutator by means of a resistance which is best suited to a given size and type of machine.

II. SINGLE PHASE INDUCTION MOTORS.

By far the greater number of single phase motors now in operation are of the induction type, such motors being manufactured by all of the large companies, though at the present time they appear to have found greater favor in Europe than in America.

The torque of these motors, as is well known, is not in evidence until the rotor has been started, and, therefore, some starting device is necessary. This, as may be noted from some of the patents previously considered, takes the form usually of an auxiliary winding in which flows a current differing in phase from that in the main winding, such difference of phase being produced by some of the various phase splitting devices heretofore considered.

One of the most successful methods employed for starting single-phase induction motors is that recently developed by the Wagner Co. of St. Louis.

The stator of this machine is connected directly across the mains. It is so wound with "pan-cake" coils threading through slots in the iron punchings as to produce magnetic poles varying in strength to zero each way, according to a sine curve, from maximum intensity at the centers.

The rotor is a direct current armature of low inductance, provided with a radial form of commutator having a short-circuited pair of brushes which at starting allow the induced currents in the rotor to exert a torque which brings it rapidly to speed. The motor thus utilizes in starting the method first employed in the Anthony, Jackson, Ryan motor, to which reference has previously been made. When the armature is at running speed the commutator is completely short-circuited by a circle of copper segments; the winding then affords a substitute for the ordinary squirrel cage form, the difference being that the currents are restricted to the paths offered by the individual coils.

The short-circuiting of the commutator segments is done at the proper speed by means of an automatic device upon the shaft within the armature, consisting of a set of governor weights acting against a spiral spring. The centrifugal force of the rotating weights at a given synchronous speed is sufficient to overcome the tension of the spring, the short-circuiting circle is forced into place, the brushes are lifted from the commutator at the same time and the machine continues to run as an induction motor.

Tests made upon these motors of from 5 to 15 H. P. by competent engineers have shown that they are applicable to any conditions other than those requiring frequent starting and stopping or wide variation of speed; and that they show very creditable values of torque, efficiency, and power factor.

The theory[11] of operation of these motors appears to have first been simplified by Galileo Ferraris,[12] though numerous contributions have since been made in amplification of details concerning it.

Ferraris' method of treatment was based on the idea that a simple alternating magnetic field, is capable of being resolved into two oppositely revolving fields, each having a frequency equal to that of the alternating field and an amplitude equal to one-half of it, and upon this method Thompson,[13] Behrend[14] and others have written.

While this substitution of two oppositely revolving fields for the simple alternating field is legitimate, it is clearly necessary to also consider the magnetic effects of the induced currents which flow in the armature.

Friedrich Eichberg[15] has developed a simple and valuable theory by assuming the single phase winding split up into two equal parts and each part connected in series with one-half of an imaginary winding producing a cross field, the two halves of the latter winding being assumed to carry currents in opposite directions, so as to produce no magnetic effect.

He refers to the fact that Steinmetz (Elektrotechn. Zeitschr. 1899 Heft 25 and 26) has abandoned the oppositely rotating field hypothesis and has deduced equations of the single phase motor by assuming a cross-field whose intensity is proportional to the rotor speed. "In reality," says Eichberg, "the cross-magnetism is not directly proportional to the speed, but a complicated function thereof," and he goes on to consider each part of the single-phase winding, plus one-half of the hypothetical winding which produces a cross field together, as a polyphase winding; the two polyphase windings produce two oppositely rotating fields. These two windings are considered to be connected in series across the mains, and the distribution of pressure is calculated according to the conditions governing the distribution of pressure when two transformers are connected in series.

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[11] Blondel, La Lum. Elec., Dec., 1893; Steinmetz, Am. Inst. Elec. Eng., 1894, 1897, 1898, 1900. Arno, London Electrician XL., 254. Field, Elec. Rev. XLIV., 194, 271, 439, 492, 579. Wiener, Am. Electrician X., 317. Behrend, Elektr. Zeitschr., Jan., 1896; Elec. World XXVII., 205. Heyland, Elektr. Zeitschr., Oct. and Dec., 1895; London Elec., 1896.

[12] Ferraris, "A method for the Treatment of Rotating or Alternating Vectors, with an application to Alternate-current Motors," London Electrician, XXXIII, 110, 129, 152, 184, 1894. Translated from a paper of Dec., 1893.

[13] S. P. Thompson, "Polyphase Electric Currents," 1900.

[14] Behrend, "The Induction Motor," 1901.

[15] Elektrotechn Zeitschr., June 14, 1900.

When the armature is in motion the effective impedance of the polyphase winding producing the field in the direction of rotation is increased while the impedance of the other winding is decreased.

The author gives several diagrams showing the graphical representation of the theory as applied to the single phase motor, which assists materially in establishing its validity.

PART TWO.

EXPERIMENTAL WORK.

Indroductory Note:—The foregoing survey of the subject indicates that the field of single-phase motor work, concerned with rotation produced in various ways, has apparently been quite extensively exploited both in practical experiment and invention, and also in the development of mathematical theories to explain the operation of such apparatus.

But the introduction in recent years of apparatus functionating through the influence of a polyphase, or rotating, field has so absorbed the attention of the electrical fraternity that the single-phase apparatus for power transmission purposes has received rather meagre consideration.

It is the belief of some authorities on the subject, however, that the polyphase motor is not a permanent apparatus, and that it will eventually be replaced by a more perfect type of single-phase machine.

In order to become thoroughly familiar with some of the single phase possibilities, the experimental work, described in the following pages was undertaken with a view to answering the question: Under what conditions is it possible to produce self-starting rotations in a simple alternating magnetic field?

The time allotted to the work was insufficient to carry it to a complete conclusion, though it is believed a sufficient amount has been accomplished to throw some additional light upon the question.

It will be evident with a little consideration that a repetition of some of the experiments of others was necessary, in order to thoroughly understand their apparatus before attempting to modify or improve upon it. The following pages deal chiefly with the experimental work in the order in which it was performed, without discussing to any considerable extent the mathematical theory concerning it.

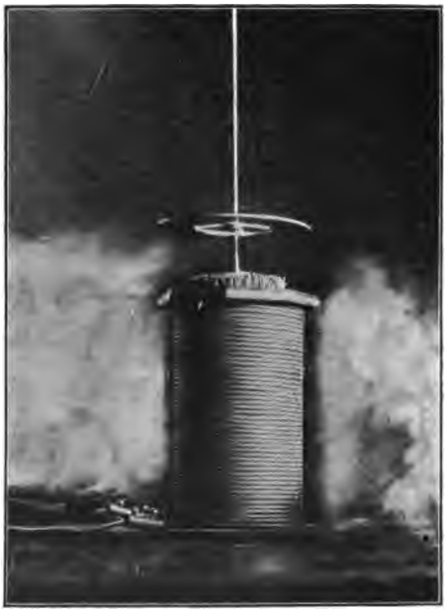

FIG. 78.

On pages 19 to 24 reference has been made to some of the experiments of Elihu Thomson and an explanation of the behavior of his apparatus is there given. Figure 78 illustrates a similar apparatus for producing repulsive effects as described on preceding pages. Single-phase alternating current passes in the coil and a rather heavy aluminum disk is supported in the air, as shown, because of the repulsive effect, the string being used merely to steady the disk in position. This effect has already been explained. Now if a piece of copper, aluminum, or other good conducting metal be held between a part of the disk and the coil, the disk at once begins to rotate.

This has been explained by Fleming, as due to the fact that the stationary metal or "shader" shields a part of the disk from the action of the pole, and hence causes the induced currents in the metal and in the disk to be so placed relatively that continual attraction takes place between them, and so produces regular rotation.

An inspection of Walker's mathematical treatment[16] of this phenomenon, however, leads one to conclude that the above statement does not fully explain it, but that the currents induced in the "shader" are caused by self-induction to lag, so that the field acting upon the disk does not alternate in one phase. A consideration of this statement made it appear possible, that if by any means a single phase current could be made to produce a constant difference of phase of eddy currents in a disk, rotation of the disk would result.

The apparatus used for some preliminary experiments in this connection is indicated by Figure 79. This consisted of two coils connected in series, carrying single-phase current, between which was placed an aluminum disk, balanced and perfectly free to turn upon an agate support. A considerable amount of time was spent upon this experiment, for in certain positions of the upper coil with respect to the lower, the disk slowly rotated. It did not seem that any "shading" effect was present, because the apparatus was apparently free from any material in its construction which could produce this effect. The disk represented in use in the figure was of aluminum, and thicker toward the center than at the margin; it appeared to possess a tendency to rotate when a rather large current (20 amperes) was flowing in the coils, and when they were in certain particular relative positions; thus it seemed possible that a difference of phase between the eddy currents induced in the disk gave the rotation, the cause of such phase difference being due to a difference between the values for the self-induction for the thicker and thinner portions of the disk.

The rotation, however, when produced at all, was always obtained with much difficulty. Disks of different shapes, and of different metals (as shown in the figure), were substituted, but the results were far from being positive. No. 1 represents an aluminum disk having a double thickness of metal at the margin, No. 2, a disk of the same metal having the inner portion removed, and No. 3 a plane aluminum disk of uniform thickness. No. 4 is a copper disk and No. 5 an iron one. Very little, if any, rotation could be produced with any of these, though precautions were taken to balance them perfectly and every possible position of the upper, movable coil, with reference to the other coil and to the disk was apparently covered. The upper coil was made of number 6 wire and the lower of number 10, and through the two in series was sent a current varying from 5 to 25 amperes, the rotation when produced always occurring with the heavier currents. Another coil of finer wire was substituted for the coil of number 6 wire and no rotation was obtained. This seemed to indicate that the results previously obtained were due to the shading effect of eddy currents produced in the larger size copper wire, of the first coil; yet the smaller wire of the second coil, of course, could not carry so large a current, and as the large coil was limited by the carrying capacity of the smaller, it was still a question as to whether the proper arrangement of apparatus would not give a positive rotary effort. In order to test more fully on this point, an aluminum disk twelve inches in diameter was turned, so that the thicker portion constituting two-thirds of the diameter of the disk should be nearly one-half inch thick, while the thinner part was one-sixteenth inch. Figure 80. This disk was fitted to a uniform glass rod for an axle mounted on four pivot wheels, as shown, in such a manner as to reduce the friction of rotation to a minimum, and perfectly balanced. A glass rod was used because a question arose as to the effect of the steel axle which supported the disks previously used in a vertical position, and every precaution was taken here to eliminate any possibility of shading effects. Two large coils connected in series were placed as shown in the figure, and also in various other relative positions; the sizes of the coils were

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[16] Phil. Trans., 1892.

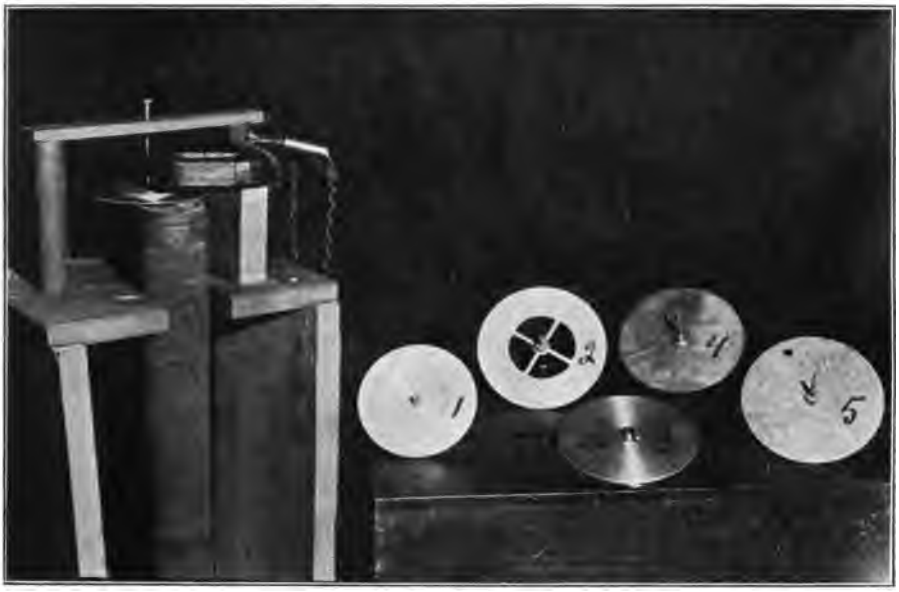

FIG. 79.

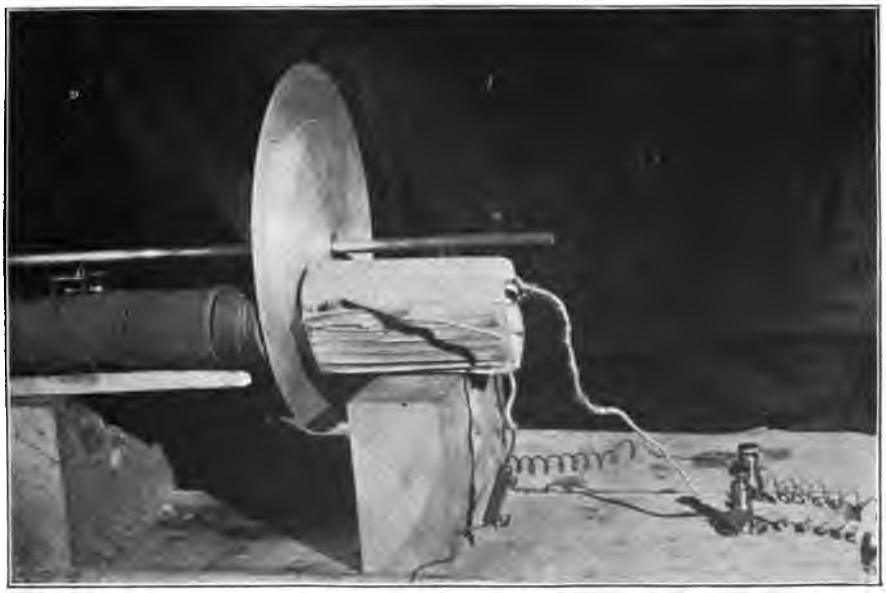

FIG. 80.

changed, and others substituted, a large coil in fact being placed in various positions over the axle on one side, while another coil was moved about on the opposite side, but so long as the coils were in series no rotation could be produced, except when a metal shader was placed over one of the coils. When two coils were connected in parallel on one side of the disk with another in series with them on the opposite side, the disk ran very rapidly, and likewise when one of the coils, of the two in parallel, was short-circuited, with the other in series on the mains but surrounding the first, rapid rotation resulted.

It appears conclusive, therefore, that the two coils in series acting upon this disk alone cannot cause it to move. It is possible that the difference of phase in the eddy currents produced in the thicker and thinner parts of the disk was not great enough to produce a rotary tendency sufficiently great to overcome the inertia of the disk. But the character of the material used and the shape of the disk was such that it does not appear that it could readily be improved upon to increase the phase difference, if but one metal be used for the whole disk; the torque necessary to overcome the friction of the apparatus was extremely small.

The results obtained on the whole appear to show that a phase difference in the eddy currents of the disk alone cannot produce rotation, since their energy is expended solely in the disk. There can be no reaction of any sort between the energy of these currents in the disk, and energy or matter outside the disk; therefore no turning couple can exist to move the disk. When a shader is introduced over one of the coils then there *does* exist a reactionary effort between the currents of the disk and those of the shader and movement results; in the case of two coils in parallel on one side of the disk and one on the other in series with them, the difference in self-induction of the two parallel coils, together with the effect of the third coil, is sufficient to split the phase of the field and so produce an imperfect rotary field the obvious effect of which is to produce rotation.

Since the force of repulsion was so pronounced in the case of the magnet coil and the aluminum disk it appeared possible to obtain continuous rotation with the magnet coil without the use of a "shader." An aluminum paddle wheel was therefore constructed as shown in Figure 81. This was balanced and mounted on a glass rod, and the whole arranged to turn on pivot wheels as bearings, with the least possible friction. The coil in the illustration was 18 cm. high, surrounding a bundle of soft iron wires 7.5 cm. in diameter, and consisted of four layers of No. 6 wire.

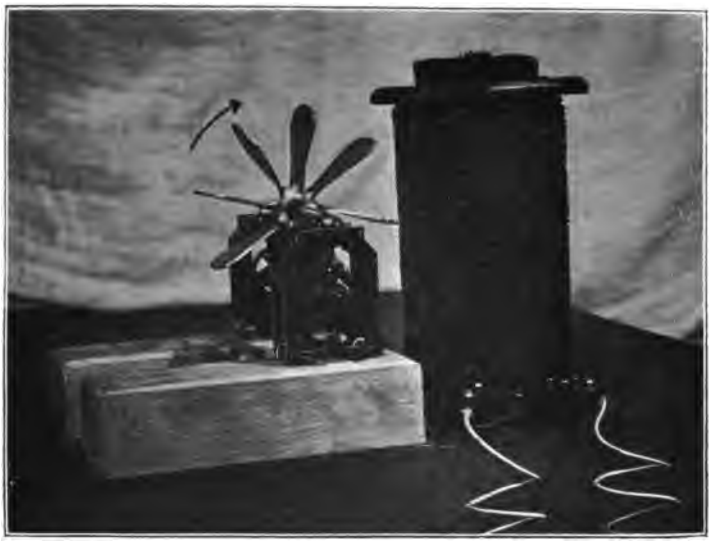

FIG. 81.

It will be noticed by the figure that the center of the wheel is placed just above the center of the coil; in this position the wheel started and rotated rapidly in a downward direction when the coil was excited by a simple alternating current. If the wheel were lowered in reference to the coil, when its axis was opposite the center of the coil it stopped, and on moving it yet lower it started again and revolved in the opposite direction whence it will be seen that it rotated always *toward* the center of the coil. This appeared to be due to the circulation of eddy currents in the paddles.

Just how these currents moved was then a question, and so the apparatus shown in Figures 82 and 83 was constructed. The blades of a two paddle wheel were turned at right angles to each other and balanced in position as shown in Figure 82. When the current was turned on the coil the paddle retained the position shown in Figure 83 so long as current flowed. The blade number 2 was next placed in the position of number 1, but no effect whatever was produced. The paddles were turned at various angles to their plane of rotation, but the most pronounced effect was obtained in the position shown, where the surface of the blade was perpendicular to its plane of rotation, and parallel to the cross-section of the coil. This clearly indicated the plane of the paths of the eddy currents in the blades. Referring again to Figure 81, it should be noted that the position of the wheel is correct with reference to the coil, to give the maximum starting torque and greatest velocity of rotation, in the direction indicated by the arrow.

A fibre hub was made so that blades of different thickness and different materials could be used, and different numbers of blades of the same material. Four, eight and sixteen were in turn inserted, but the rapidity of rotation was not appreciably affected, the rate being about 30 revolutions per minute for the aluminum blades 2 mm. thick, when the current in the coil was 60 amperes. This speed was the constant one after the wheel had been in motion for a short time; the number of revolutions for the first minute, the wheel starting itself from rest, averaging about 16. Copper blades of the same thickness as the aluminum were tried and it seemed that the speed was a trifle slower, and when reduced in thickness by one half, the speed was almost proportionally reduced. Copper wires, used in place of blades gave no rotary effect, and iron blades were also useless. The iron blade wheel simply oscillated and hummed in any and every position in which it was placed.

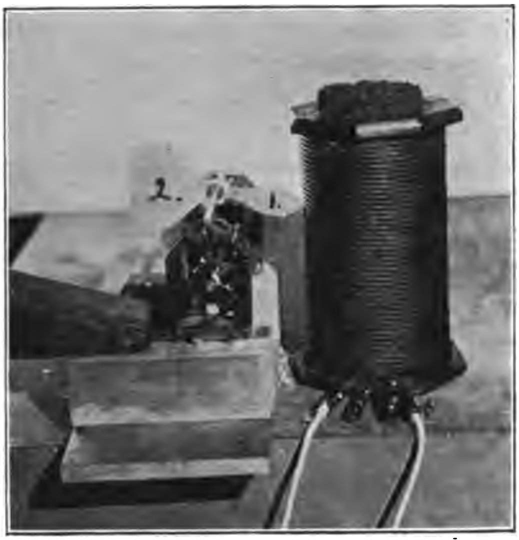

FIG. 82.

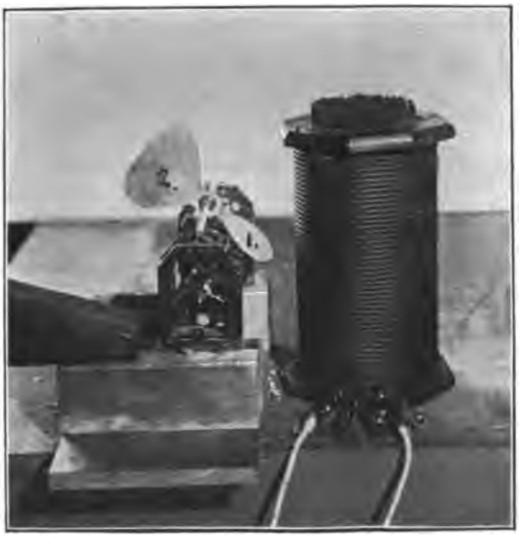

FIG. 83.

In order to determine whether the iron core was necessary to produce the rotation of the aluminum and copper wheels, a larger coil was constructed of No. 10 wire, having a wooden core, and so designed as to admit the maximum current which the wire would carry for short intervals when connected across a 220 volt alternating current circuit. No place could be found relative to this coil when so used, where rotation occurred, unless a shader were interposed between it and the coil. This coil, however, had the disadvantage that the magnetic field produced by it was considerably weaker than that obtained with the iron core coil and so the result was still unsatisfactory. As a final test of the question a larger coil was evidently necessary.

Through the kindness of Mr. Chas. H. Williams of the Madison Gas and Electric Co., two 1000 volt generators of 63 and 125 frequency respectively, were placed at the disposal of the writer for use upon this experiment. A coil having an air core was therefore designed to be placed directly across the 1000 volt terminals, and when so placed to admit a current of 60 amperes, at 63 frequency, and thus produce a powerful magnetic field without the use of an iron core. The coil was formed upon a wooden core 25 cm. long and 8 cm. in diameter, the core being of such form as to be easily removed, and consisted of 1000 turns of No. 8 single covered magnet wire. When completed the coil had a mean radius from the centre, of 11 cms. approximately, and a resistance of about 1 ohm. It was presumed in designing, that this wire would safely carry 60 amperes for short intervals of time. The coil when placed on the 1000 volt 60 frequency circuit was found to hold the current at 59 amperes approximately, and the aluminum paddle wheel which had previously been used with the iron core coil, was placed in various positions, but no positive rotation could be obtained. The coil was also inserted in the 1000 volt 125 frequency circuit but could not be induced to set up a continuous rotation of the aluminum wheel. The ampere turns of this coil was calculated to be fully three times that of the smaller coil having an iron core, and so it seems that rotation should have occurred had there been a sufficient reason for it. It is clear therefore that the core of the former coil played a part in the rotation of the wheel, and its action is probably due principally to the effects of magnetic saturation and hysteresis.

It does not seem entirely improbable, however, that the core acted in the capacity of a shader, and a satisfactory way of settling that point would be to use a coil having a large core of aluminum or copper, which, unfortunately, could not be obtained at the time the experiment was in progress. Until that point is determined it is hardly possible to give a conclusive explanation of the ultimate cause of the rotation observed.

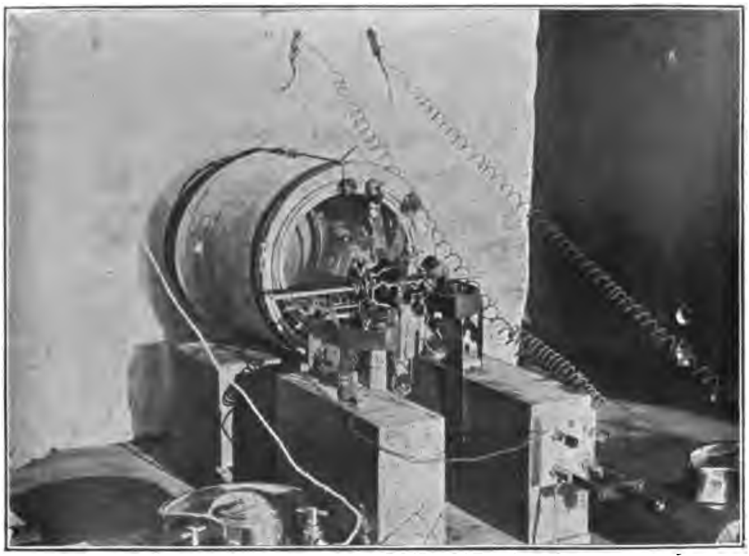

FIG. 84.

A portion of the large coil used on the 1000 volt circuit was next removed, leaving the coil as represented in Figure 84. The coil wheel also shown in the figure was made by winding a number of little coils of No. 28 copper wire, and fastening them with wax to glass spokes which were in turn inserted in the fibre hub used in previous work. These coils were all alike, having 242 cms. of wire wound into 63 turns, and the whole wheel with a true glass rod for an arbor was carefully balanced in the position shown by means of wax. The coils were first short circuited each on itself, but no rotary effect was obtained when current flowed in the large coil. The small coils were then connected altogether without producing any effect, except when a shader was interposed between them and the opening in the large coil.

This wheel was subsequently tried in the position as shown by Figure 85 and again rotation was readily produced without any shader, whether the little coils were connected as individuals or in series.

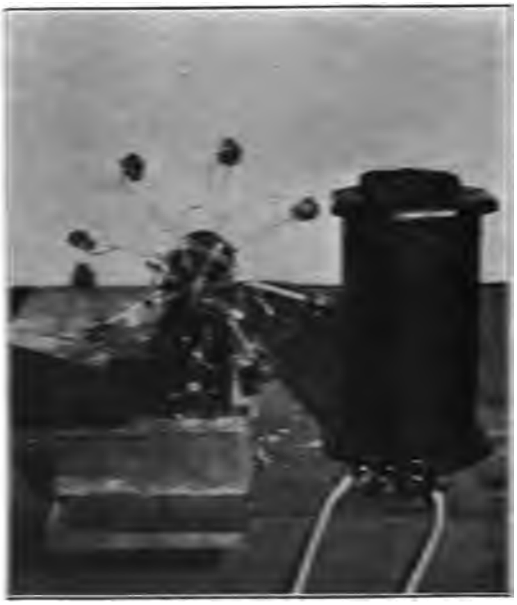

Fig. 85.

An apparatus was made for testing the phase relations between the currents in the little coils with the idea of affording an explanation of the rotation. This apparatus or phase changer, consisted of two small transformers, each wound with the same number of primary and secondary turns. (Fig. 86.) Each transformer had its secondary winding divided into twelve equal sections, and taps brought out from each section to binding posts, so that with 104 volts on primary each transformer gave 96 volts on the full secondary, with the possibility of decreasing this pressure by 8 volt intervals to zero. The primary coils of these transformers were to be connected one in phase A (Figure 87) and one in phase B with a 2-phase, 60 cycle circuit, and the secondaries having the divided windings were arranged so that their terminals could be jointly connected so as to supply pressure at various phases, from 0 degrees to 90 degrees away from either phase A or B.

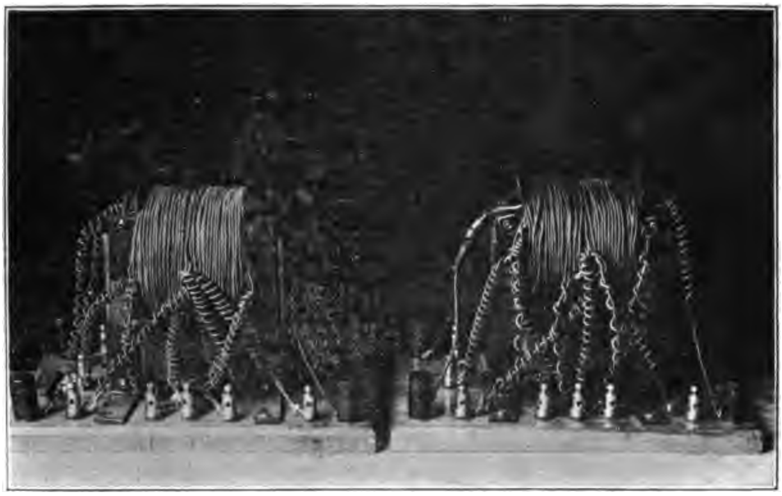

FIG. 86.

The diagram shows the arrangement of connections, T_1 T_2 being the transformers connected with two phase alternating current, one phase of which passes through the large coil C.

The secondaries are connected together through a few lamps and the current coil of a low reading wattmeter. The test coil is connected to the pressure coil of the wattmeter, and for different positions along the large coil the pressure developed in the test coil is balanced by changing the combination of the transformer secondaries.

Referring again to Figure 84, a portion of the apparatus yet unmentioned is that for connecting the small coils by means of an improvised commutator with the external circuit through a non-inductive resistance and a coil also whose reactance could be varied as desired, the whole in derived circuit to the large coil. This, as will readily be seen, really amounted to a form of alternating shunt motor, but having no iron whatever in its construction. The wheel ran very rapidly, when the eight coils were so connected by means of the mercury commutating device, as to give four in parallel at the same time, and the speed could be varied nicely by changing the reactance of the armature circuit. An application of this effect, though of small importance, was made by adapting a small direct current bipolar motor to operate on an alternating current circuit. The three coils on the armature were rewound so as to connect one end of each to one segment of a commutator and the other ends to a collector ring which had been fastened to the shaft. The diagram (Figure 88), shows the connections, the circuit to the armature being in shunt, to the main connections. The current passed in at two brushes connected together and bearing upon the commutator as shown, and out at the third brush bearing upon the collector ring. This arrangement of having two of the three

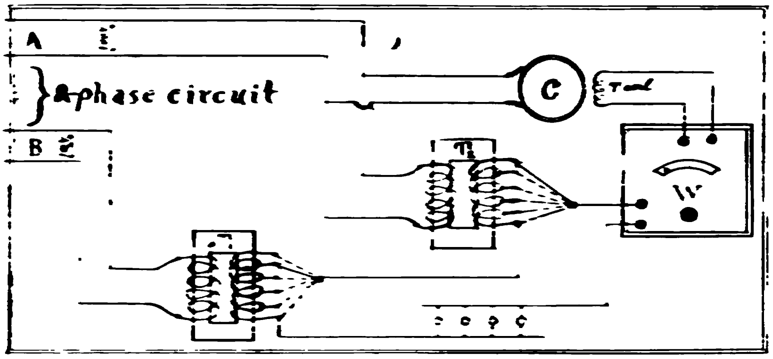

FIG. 87.

coils in action all the time gave a greater starting torque and higher velocity by far, than when only one brush bore upon the commutator, and one coil was in action. The motor being small no tests could readily be made upon it, though it showed a strong starting effort and ran apparently close to synchronism,

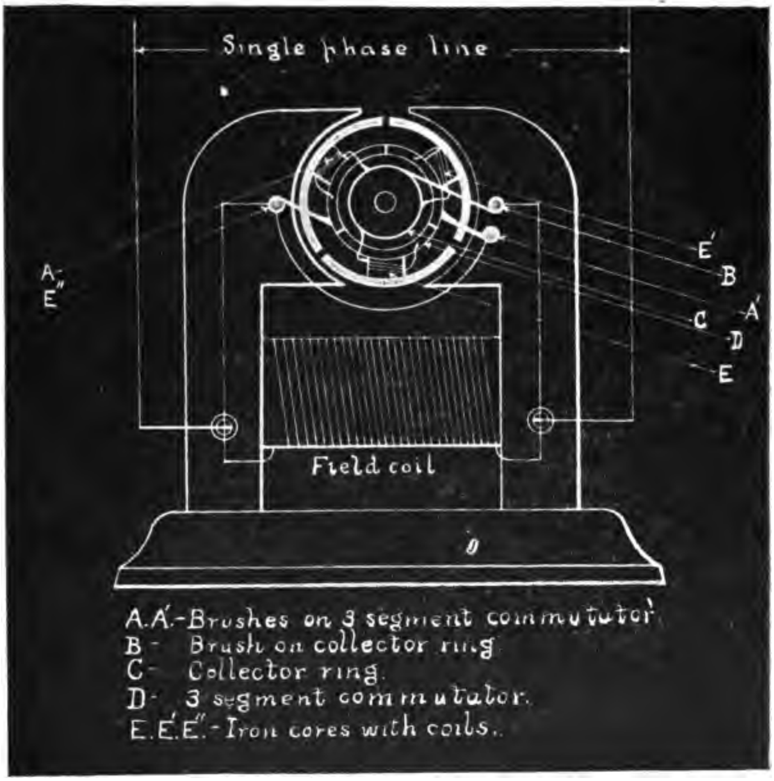
Single phase line
A-
E″
E′
B
C
A′
D
E
Field coil
A.A′.-Brushes on 3 segment commutator
B - Brush on collector ring
C - Collector ring.
D - 3 segment commutator.
E.E′.E″.-Iron cores with coils.

FIG. 88.

without sparking in the least. It did not seem advisable, however, to construct a larger piece of apparatus on this basis, first because time and facilities were not at hand for doing so, and secondly, because commutating motors were not within the immediate limits of this investigation.

Attention was therefore turned at this point to the investigation of the possibility of producing rotation in a single phase field without the use of a commutator, and without having any metal in the apparatus that could possibly produce shading or magnetic lag effects.

The first apparatus consisted of two Dimond meter coils held by a wooden support, and so placed as to produce a field across a 3 inch space from one to the other. An armature was made of two coils wound on wooden rings as shown by (Fig. 89), the rings being movable with respect to each other so that they might be placed at any desired angle. The armature coils were both short-circuited in the first trial, and single-phase current sent through the field coils, but it was at once seen that the field was too weak to give any positive effects. Two large coils of equal dimensions were therefore made for the work and were designed to be placed on an alternating current circuit, of 155 volts and 60 frequency in series with each other, and to hold the current at what was considered the maximum carrying capacity of the

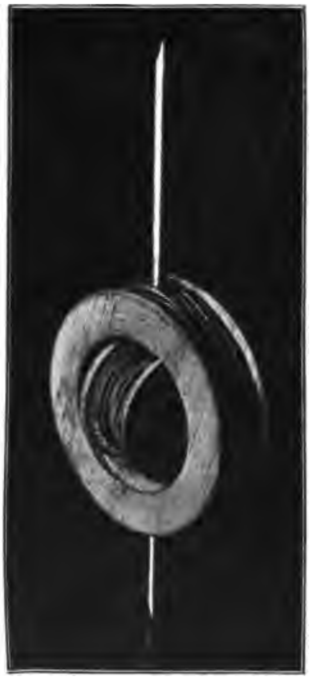

FIG. 89.

copper wire used, for short intervals. Number 8 double cotton covered wire was used and presumed, as in the previous case of the 1000 volt coil, to carry 60 amperes. The dimensions of each of the coils was as follows:

Length—20. cms.
Mean Radius—6.75 cms.
Turns per cm.—2.25.
Turns per layer—45.
Number of layers—6.

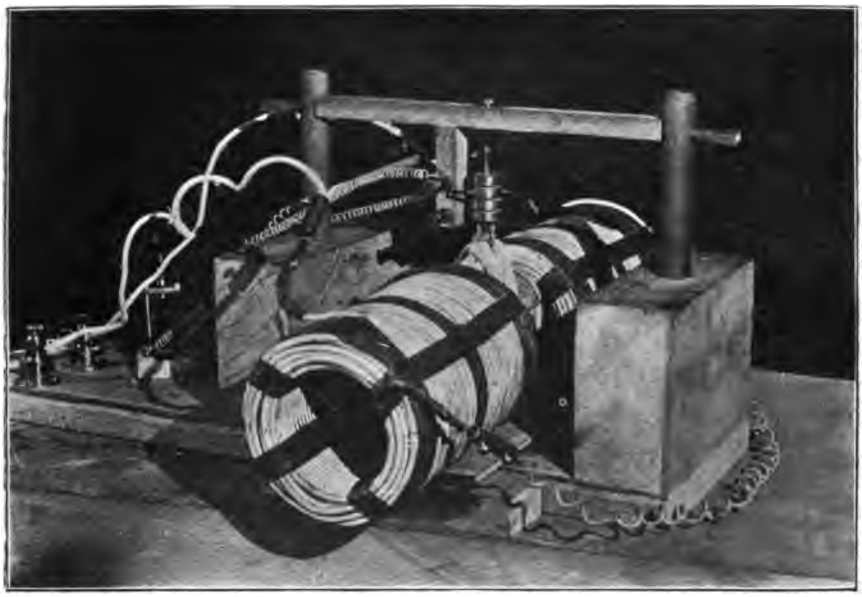

FIG. 90.

The current in these coils when connected up in series on 155 volts showed an instrument reading of 57 amperes. This gave a very strong magnetic field, and in this field between the two coils arranged as shown in Figure 90 was placed the two coil armature of Figure 89. Various experiments were carried out with this apparatus.

1. The coils were each short circuited and placed in different positions relative to each other, but the combination always came

to rest in such a position that a line connecting the centres of the two field coils bisected the mechanical angle between the two armature coils.

2. Coils of different self-inductance were wound upon the two wooden rings, each coil in two sections and so designed that connections could be made to give either the outer or the inner coil the greater inductive value. Again the same results as in 1 were obtained.

3. An iron core was next introduced into one of the field coils and continuous rotation was set up. This doubtless was due to a "magnetic lag" effect such as that noted on pages 61 and 62. A mass of aluminum was placed over one of the poles and again rotation was produced, resulting presumably from the "shading effect."

4. Four collector rings were next fastened upon the shaft and connection made with them and the two armature coils. Various combinations of short circuiting one of the coils, and sending current from the external circuit into the other were instituted, but the general effect was similar to that obtained in 1. This is readily explained. If we consider the two coils, which we will call (a) and (b), of the armature placed at right angles to each other, and let (a) be the short circuited coil, then (a) would stand, if it were not influenced by coil (b), so as to encompass the least number of lines of force, or with its plane parallel to the lines of force in the field. Considering (b) now carrying current from the external circuit, if not influenced by (a) it would obviously place itself with its plane perpendicular to the direction of the lines of force in the field. Therefore the resultant effect of both is to place the combination in some intermediate position between that taken by (a) or (b). The armature, however, always takes the same position with respect to one of the field coils, for any given current sent into (b) because such current gives a polarity to that coil, and the coil (a) is neutral in this respect.

5. Both coils were connected to the four collector rings, and a variety of values of current sent into each with respect to the other and the angle between the coils changed also. At first the

E.M.F. of 155 volts was used with a lamp bank to cut down the current, and again the coils placed themselves so that a line parallel to the lines of force in the field bisected the angle between the coils, when the turning effects were equal; or passed somewhere between the coils when the turning forces were unequal, a given point on the armature always coming to the same position for a given combination of current values, as if polarized.

The two transformers used as a phase changer, previously described, were now introduced into the same circuit supplying the field, and from the secondary of each, current was sent into either of the two armature coils. The E.M.F.'s of these currents was varied by connecting to different taps on the secondary, and on two occasions the armature started and rotated very rapidly. It appeared at the time to be a singular fact that these conditions could not be repeatedly obtained in such a manner as to be able to draw conclusions in regard to the rotation produced, but such was the case, and the rotation had to be ascribed to the effect of sparking which took place at the collector rings; the idea being that the circuit of one coil was broken at just the proper instant in a revolution to enable the other to keep the armature turning and so continuous rotation proceeded. Continued experimentation, however, seems to have finally led to a proof that this explanation was erroneous.

Inasmuch as the movement of the two coils with respect to each other did not produce any peculiar results, it seemed better to construct an armature having the two coils of the same size and fixed with respect to each other. A wooden ball was wound with the two coils at right angles to each other; these had the same number of turns on each, and were connected up to four collector rings as shown by Figure 91. The same field apparatus as shown in Fig. 90 was employed and an attempt was next made to produce rotation of the wooden ball armature by introducing 2-phase current into the armature coils; the field was first excited by a direct current, and afterward by a single phase current, while 2-phase passed in the armature coils, but continuous rotation could not be produced in either case. The armature came to rest always so that the angle between the coils was bisected by a line from centre to centre of the field coils. In order to try all possible combinations in connection with this device, the city single phase current having a frequency of 63 was put on the field coils while the 2-phase current of the armature was taken from the laboratory generator at a frequency of 60. Immediately a curious effect was noticed, viz., an interrupted or jerky rotation of armature. At times the rotation was in one direction, then became nil, then perhaps started backward; running rapidly, slowly, or becoming motionless, all in very brief intervals of time.

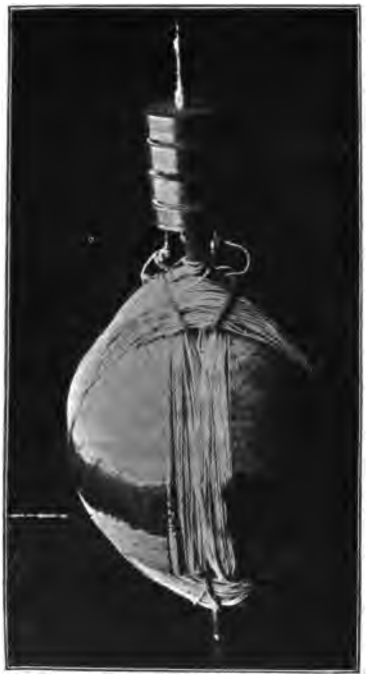

FIG. 91.

It was evident that the effect must be due to the difference of frequency in the two circuits, since the same experiment had already been tried when both circuits were taken from the same generator. In order to explain this effect we will call the plane of the field coils (or a plane perpendicular to the lines of force extending from pole to pole) A., and (b) one of the two fixed coils on the ball. Now, as has been previously intimated, if both the field coils, and (b), carry current impressed from the external circuit, (b) will take a position with its plane parallel to the plane A. If the current in the field coil and in (b) be now reversed with respect to each other the coil (b) will come to rest in a position 180° from its former position; such relative reversal of currents is equivalent to a change of phase by 180°, which is immediately evidenced by a change of 180° in their mechanical relations. If instead of reversing the relative direction between the currents in the field and coil (b), we gradually change the phase of the current in one (we will say in b), it is obvious that when the phase difference reaches 90° the coil will be in a neutral condition, or the magnitude of the turning couple between the field and the coil becomes equal to zero. Now suppose again that the fixed coil (c), upon the ball, is wound so that its plane is at an angle of 90° with the plane of (b) as indicated, the turning axis of the ball passing the same way through both coils. If a 2-phase current be passed into the coils (b) and (c), in which case their phase difference is always 90°, and one of the two phases be impressed upon the field at the same time, it is evident that one of the coils (say b) will be parallel to A, because the force between it and the field is zero, when the force between the other coil (c) and the field is a maximum. So that it is clear that every change of 90° difference of phase between the field current and the current in the movable system results in a corresponding mechanical change of 90°. If the phase difference between the field and either coil is less than 90°, then the force acting between the field and the one coil is greater than zero, and between the field and the other coil, less than a maximum, so that the movable system finds a position of equilibrium somewhere intermediate between (b) parallel to A, and (c) parallel to A. Further, the direction in which the system moves for any given change will obviously depend upon whether the phase change is relatively positive or negative.

In Figure 92,

Let $\alpha =$ angle between AA′ and bb′, the plane of the field and one of the coils.

Let $\beta =$ electrical angle between the currents in AA′ and bb′.

Let $90^\circ =$ electrical angle between the currents in bb′ and cc′.

Let $90^\circ =$ mechanical angle between the coils bb′ and cc′.

Assuming the ampere turns on bb′ and cc′ equal, the self-induction in these coils to be zero, that we are dealing with sine wave effects throughout, and that all induced E.M.F.'s are negligible, we may write:

$T_b = k \sin \alpha \cos \beta$ and

$T_c = k \sin (\alpha + 90^\circ) \cos (\beta \pm 90^\circ) = \pm k \cos \alpha \sin \beta$, where

$T_b =$ torque acting on bb′

$T_c =$ torque acting on cc′

When the system is in equilibrium,

$T_b + T_c = 0$, or

$\sin \alpha \cos \beta = \pm \cos \alpha \sin \beta$ and

$\tan \alpha = \pm \tan \beta$ whence

$\alpha = \pm \beta$ or $\pm (\beta + 180^\circ)$,

the double sign showing that the direction of the motion of α relative to β depends upon the sine of the angle between the currents in the two coils. The two values 180° apart are points of equilibrium in the cycle. If the electrical angle between the two armature coils is not 90° then we have

$T_b = k \sin \alpha \cos \beta$, but

$T_c = k \sin (\alpha + 90^\circ) \cos (\beta \pm \gamma)$ where

γ is equivalent to 90°.

Then at equilibrium

$\tan \alpha = \pm \sin \gamma \tan \beta - \cos \gamma$

whence it is evident that when

$\beta = 90^\circ$, $\alpha = 90^\circ$ and when

$\beta = 0^\circ$ or 180°, $\alpha = \gamma - 90^\circ$ so long as γ is not greatly different from 90°, and the maximum difference between α and β occurs near the point where $\alpha = 0^\circ$ or 180°.

From this discussion it is obvious that so long as the frequency of the field circuit and of the armature circuits was the same a position of equilibrium would at once be taken by the armature and no further movement take place, which was the case when the currents were taken from the same generator.

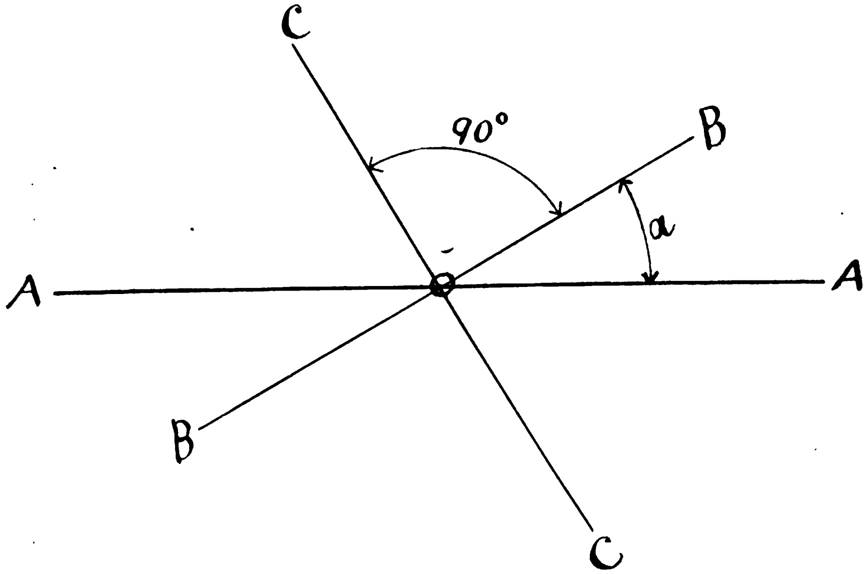

FIG. 92.

When the city circuit was turned into the field, however, the frequency differed normally by three cycles per second from that of the laboratory generator and so rotation of the system slowly began. The obvious explanation of rotation being forward, backward or nil, is that the frequency of the lightly loaded laboratory generator was practically constant at 60, while the frequency of the city circuit due to irregularities of load, while normally above 60 (when the movable system rotated), at times dropped to 60 (when the system stopped), or even fell below 60 (when the system rotated backward).

Having thus discovered what appeared to be a serviceable apparatus as a synchronism indicator for paralleling alternators, the writer learned shortly afterwards that apparently the same device had been patented in October, 1901, by Mr. Paul M. Lincoln,[17] then of the Niagara Falls Power Co., as a synchronism indicator and frequency indicator. As a synchronizing device this apparatus has found great favor with the large electric power plants and particularly in the Niagara Falls Plant for which it was first designed, it being far superior to the old apparatus (synchronizing lamps) because it shows,

1. Whether the machine being synchronized is running too fast or too slow, and
2. The exact point of synchronism.

It appears, however, that a slight modification of this apparatus can be made very useful as a power factor indicator, or phase meter, though so far as the writer is able to learn from Mr. Lincoln, or the General Electric Co. (who manufacture the Lincoln synchronizer), such an apparatus has not as yet been manufactured for that specific purpose.

Referring again to Figure 90, it will be noticed that the armature there represented consisted of three coils, having an equal number of turns. These were wound so that their planes made 60° angles with one another, and the three coils were connected to three collector rings, with their free ends joined together so that the whole constituted a regular star connected winding. This armature was placed in the field, Figure 90, as shown, in which a direct current circulated. A 3-phase current was sent into the armature and it was found to be self-starting and capable of attaining a considerable speed of rotation, the entire structure being devoid of iron, or shading effects, or commutating effects. Then single phase current of the same frequency as that in the armature coils was sent into the field, but no continuous rotation could thus be produced.

At this stage of the work it seemed advisable to obtain a field that would be more homogeneous and in which the large air gap could be reduced between the armature and the field. Accordingly a laminated iron ring was procured having its

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[17] See article by Paul M. Lincoln, presented at 18th annual convention of the Am. Inst. of Elec. Eng., at Buffalo, Aug., 1901.

Mean circumference = 15 cms.
Cross-section = 9 sq. cms.

It was decided to use No. 18 D. C. C. magnet wire for the winding and the coil was then to be of such impedance that when placed on 100 volt circuit the current should not exceed 6 amperes. Calculation showed the number of turns required to be 1,273. It further seemed desirable to so wind this ring that either two, four or six poles could be obtained in the field, and it was so made having,

Sections	12
Turns per section	105
Total turns	1260
Resistance of one turn	.026 ohms

The appearance of this ring as completed, having taps coming out between each two of the twelve sections is represented by Figures 93 and 95. With the arrangement of apparatus shown in Figure 93, a number of experiments were performed, the most significant of which are briefly described as follows:

1. The field coils were so connected up and excited by a direct current as to give a bipolar field, one pole being at either end of a diameter of the ring. Three-phase current was then sent through the armature coils and a good starting torque was obtained and rapid rotation continued.

2. Single-phase current was next sent into the field; and 3-phase into the armature coils, as before. In this case the armature started from certain positions and developed a rapid rotation (500 r. p. m. approximately). In other positions it would not start, but by some juggling of the switches of the different circuits it could always be made to start, and when once started rapid rotation continued uninterruptedly. It was furthermore always positive in its direction of rotation when once thoroughly started, i. e., it could not be made to rotate in the opposite direction unless the connections to either the field, or to one phase of the armature circuit were reversed. The velocity of rotation was noticeably more uniform when a balanced condition of currents existed in the 3-phase coils.

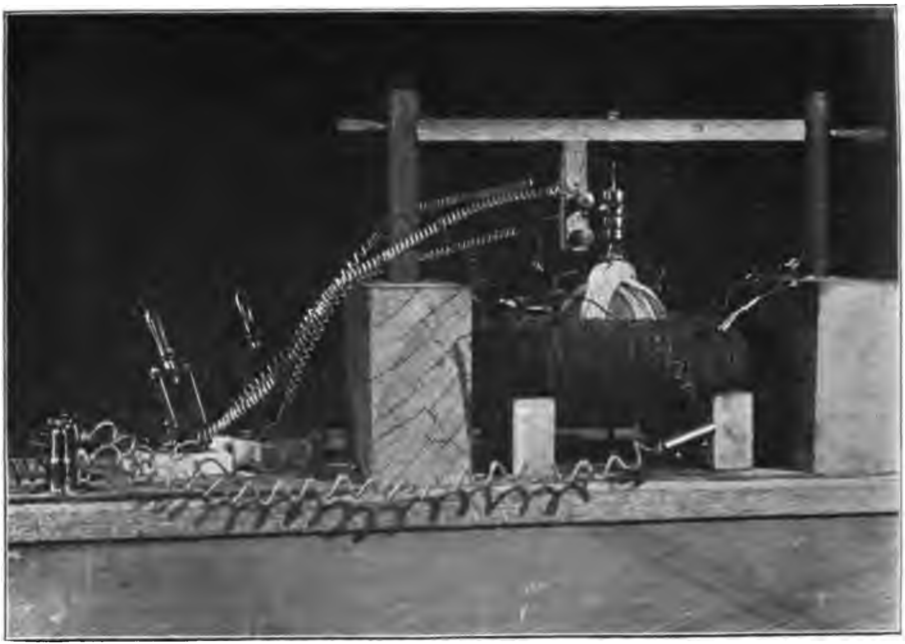

FIG. 93.

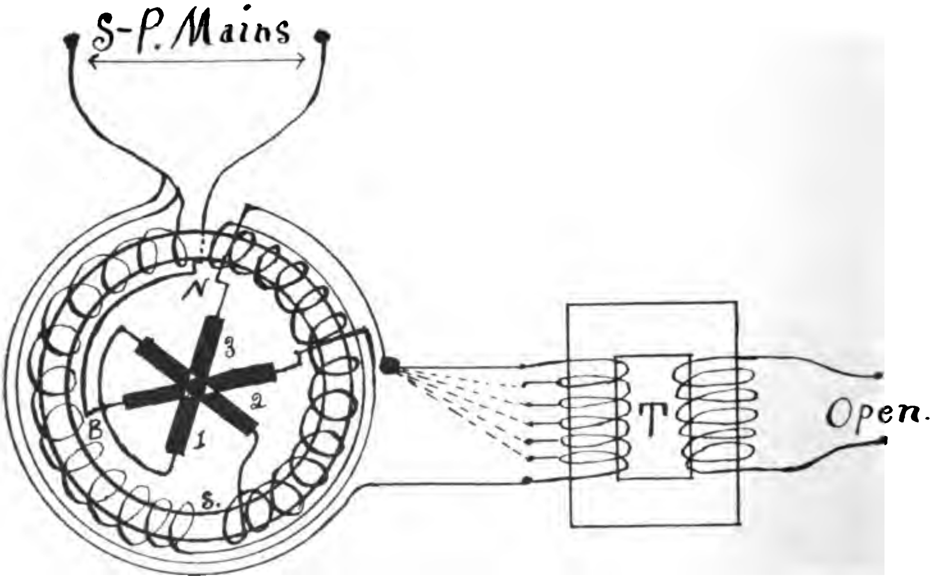

FIG. 94.

3. One phase of the 3-phase current was next sent into the field coils with 3-phase in the armature as before, and a similar rotary effort was obtained. No extended data on the E.M.F.'s or currents in the separate circuits could be obtained because the large currents which were required in the armature to produce rotation heated it extremely hot in a short time. An air-gap of nearly one cm. existed between the armature and the field coil, which may account to some extent for this large current required to produce continued movement. It was also observed, however, that rotation was not possible if the field was too strong; in other words there appeared to be a critical point in the field excitation where the rotary effort was at a maximum for a given current flowing in the armature coils.

Another point of some interest in this connection was made evident by the burning up of the coils, which necessitated the rewinding of the armature. When the connections were again made to the collector rings, they were so made as to allow each phase of the current at any given instant to traverse each of the three coils in the same direction, but when the armature was subjected to the same conditions as before, it could not be made to rotate. A little study of the matter, however, elucidated the fact that the coils must be so connected to the collector rings as to cause the current at any given instant to be flowing in one of the coils in one direction, in the next coil, in the *opposite* direction, and in the third coil in the same direction as in the first; when so connected rotation was readily produced as before.

4. 4-pole and 6-pole fields were next used with conditions remaining the same. With 4-poles the speed of rotation was greatly diminished, and with 6-poles no rotary effort was exhibited; the reason for this may have been due to the fact that the field in this case was too weak, but that point was not investigated.

5. An attempt was next made to produce rotation by connecting the apparatus as shown in diagram, Figure 94. When thus connected, a very rapid rotation of the armature was set up,

but the results were not conclusive because of the collector rings being badly burned, and the vicious sparking which occurred. Later on, the collector rings and brushes were put in proper condition, but with apparently the same conditions as before the armature could not again be made to rotate. An unreasonable amount of time, in fact, was spent in trying to produce the former conditions for rotation but to no effect.

6. The next method employed was that of so connecting the armature coils that one could be short-circuited, a second, connected through a variable self-inductance, and the third connected through a condenser. This idea was carried out in order to produce if possible, a 3-phase effect in the armature, by the inductive action of the single phase field. The E.M.F. induced in the armature coils on short circuit was only 1.5 volts so that the ordinary plate condenser was useless to produce the expected result.

By employing a new form of electrolytic capacity recently developed by Professor Trowbridge and Mr. Walcott[18] of the University of Wisconsin, however, the rotation was obtained. It was with great difficulty, however, that stable conditions could be maintained, largely due to the fact that at the time of the experiment the condenser was not perfected, and so the rotary effects perhaps should not be classed as perfectly positive. They are here mentioned simply to point out one of the apparently possible methods of producing rotations in a single phase field.

7. The field coil was subsequently surrounded with a coil, divided into three parts; one part covered one half of the field and its terminals were coincident with those of the two polar windings of the first field; the other part was divided in half, thus giving six terminals; these coils were made of No. 14 wire, one of them having 168 turns and the other two, 112 and 56, respectively. Three of these were connected together, and the other three connected to the three armature coils. When single phase current passed in the primary field winding, the induced

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[18] See paper by Trowbridge and Walcott, read at the meeting of the A. A. A. S., 1902.

currents of the secondary coil in passing into the armature gave it a rapid rotation.

8. Still another method was that of short-circuiting the secondary coil in two parts so as to produce poles directly over the primary poles, had the two coils been passed of equal self-induction. The armature coils were then all short-circuited, and again rapid rotation was produced, and a good starting torque as well. It is obvious that the last two experiments given embodied conditions of the split-phase type, though the arrangement of windings is different from the common.

After looking over the results of the experiments thus far considered, and attempting to explain the results in each case, it occurred to the writer that it might be possible to make use of the fact, previously indicated, that a short-circuited armature coil comes to rest with its plane in one position, in a bipolar alternating field, while the plane of a coil in equilibrium carrying current from the primary circuit under the same field conditions is at right angles to that of the short circuited coil.

Consider two short-circuited coils, A and B, of equal dimensions fixed at right angles to each other and constituting a movable system in such a field. Now suppose the maximum E.M.F. which can be induced in one (say A) is known, and equal to E; the E.M.F. of the other at the same time is O. Next suppose that when the system is thus placed, current from the external circuit is sent into each coil, such current having an E.M.F. equal to the value of that which would be induced, and opposite in sign, or — E. It is obvious that this E.M.F. must oppose the induced E.M.F., from a consideration of transformer principles. Therefore the situation obtains that the coil A, which has its plane perpendicular to the lines of force of the field is inactive, while a turning moment is exerted upon the coil at right angles to it. Now as B begins to turn, its induced E.M.F. begins to balance the impressed E.M.F. and at the same time the induced E.M.F. of A becomes less until finally we have the coils in a position shown by the diagram (Fig. 95), with respect to the poles N and S, the armature in this position behaving of course as though it had a south pole at S, and a north pole at N opposite (not shown). Now it will be remembered that reversing the relative direction of the current at any instant in the coil of the armature with respect to that in the field, changes the mechanical position of the coil by 180 degrees. It is therefore evident from the diagram that if the currents in both coils be simultaneously reversed with respect to that in the field, the armature will suddenly fly around to the opposite position. This it does, and something more—it continues to rotate with rapidly increasing speed till a definite number of revolutions per second is reached depending upon the value of the E.M.F. which is turned in from the circuit to balance the induced E.M.F. of the armature coils. If now the impressed pressure in the armature circuit be raised relative to that in the field, while the armature is running, the speed readily passes to synchronism and is thus maintained.

Considering now the diagram (Fig. 93) in detail. The field is made up of the laminated iron ring wound with one continuous coil of 1260 turns of No. 18 wire as previously indicated, with taps I, II, etc., leading out from between each two sections, and so connected to single-phase mains M, as to give two poles at N and S respectively. The armature has two coils of 300 turns each of No. 28 wire wound upon a wooden ball, as shown, each coil being connected to a pair of slip-rings, which are in turn connected with two double pole, double throw switches A′ and B′ in such a manner that the direction of the current in either or both coils may be reversed with respect to the direction of the current in the field coils. To supply current to these two coils it will be seen that for the coil A, current enters the switch A′ from one of the mains which is connected with the point x at the N-pole of the field and after passing through the coils returns to a brass ring R′ of a special switch or manual contact maker into the first loop or tap I′ on the field away from the pole N; the other similarly is connected to the other main through the switch B′, the current passing through the coil B and back through the ring R to the contact I on the field diametrically opposite to I′.

The operation of starting then consists merely in closing the switches A′ and B′, as shown. The main switch is then closed. If the armature happens to be in the right position, it starts and runs quickly up to speed. If it is in any other position it will move to a stand-still in a position diametrically opposed to the starting position. If now *both switches,* A and B, *are thrown together* over to the opposite contacts, the armature starts and runs quickly to speed. If now the contact maker be moved so as to complete the circuits II′ II′, II II; III′, III′, III, III, et cetera, the speed of the armature runs close to synchronism apparently, on the circuits giving the highest E.M.F.'s in the coils. It should be noted that a better arrangement for connecting the armature coils to the mains at starting would be to have the two switches A′ and B′ as one switch, and then no difficulty whatever would obtain in endeavoring to close both circuits *simultaneously.* An insufficient amount of time has prevented the investigation of all the possibilities of this apparatus. It, however, appears to be a self-starting strictly single phase motor-device, requiring positively no rotary field, magnetic lag, split-phase, eddy current, or commutating device for starting it. Moreover, so far as the writer has been able to learn by consulting the history of single phase motor design, it possesses features distinctively different from any that have been hitherto recognized.

Perhaps the explanation given thus far does not distinctively show the reason why the apparatus is believed to be independent of any of the common starting devices, and, therefore, it may be well to further indicate some of them.

1. As to the question of the existence of the rotary field.

To answer this single phase current was sent into the field, which is bipolar, and is produced by a single primary coil; at the same time use was made of the two little transformers (Fig. 84) with subdivided secondaries, having their primaries connected to the mains; current of E.M.F. equivalent to that which might be taken off the field in accordance with the diagram (Fig. 95), which is very nearly equal to the E.M.F. that would be induced in the armature coils if they were short-circuited, was sent into the armature coils from the transformer secondaries, with exactly the same results as though taken from the field, as shown in the figure.

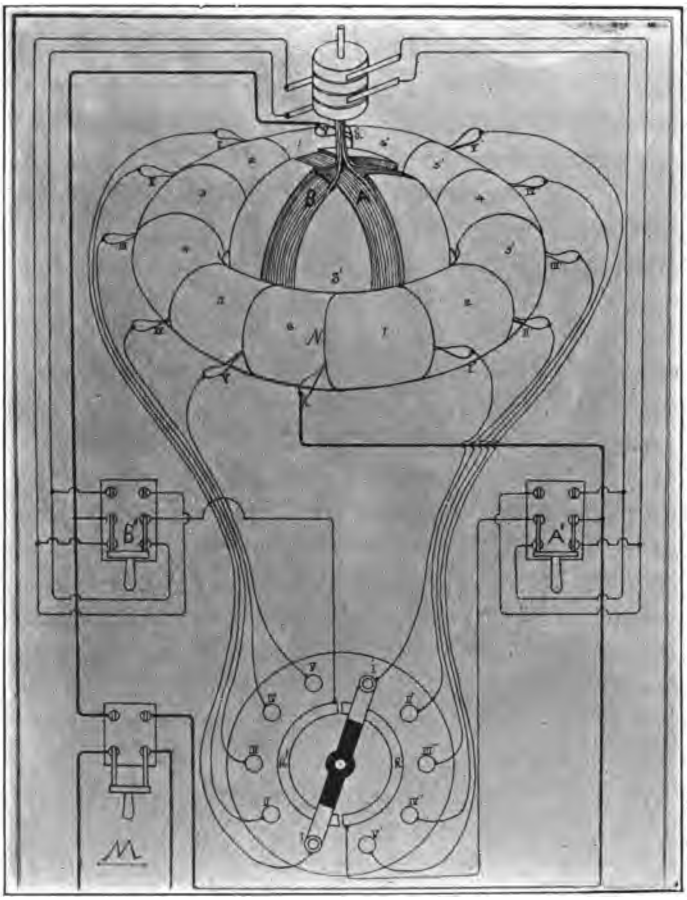

FIG. 95.

2. As to a magnetic lag or an eddy current effect.

The field is a symmetrical laminated ring made up of iron stampings and the rotor core is a wooden ball.

3. As to a split-phase effect,—the statements in 1 and 2 above are sufficient, and

4. No commutating device is used, and the slip-rings run absolutely sparkless at the start, and subsequently as well.

A complete explanation of the principle involved, however, can scarcely be attempted here since more time is necessary to complete a full investigation of the conditions which obtain, but the results appear at present to show that the starting effect is one involving a difference of relative frequency in the circuits.

A scheme of cutting the wooden ball in half and introducing a two inch soft steel ball (Figure 96) inside, and subsequently rewinding as before, has been tried, with the result that the starting torque is somewhat improved, and the currents in both armature and field to produce a given speed is decreased by about 50 per cent. The current used in the field coils to produce the result given was 4.5 amperes when the soft steel ball was used as a core in the rotor; and the rotor current was between .5 and 1 ampere. This gave a surprisingly large torque at speed, when it is considered that the air-gap between rotor and field was nearly one centimeter.

FIG. 96.

Finally one more point may be noted, viz., the speed of the armature can be regulated over a considerable range below synchronism, and, further, a switch might readily be inserted in the rotor circuits such that when a speed near synchronism is attained, the rotor coils could be short-circuited and the apparatus operate as a synchronous motor.

The experiments described in this paper have been chiefly those bearing upon points connected with single-phase work which have not hitherto found consideration in the literature on the subject. An attempted explanation of the causes for all the results obtained would unduly burden this paper and therefore such has not been included. These experiments have sought to answer the question, as previously stated:

Under what conditions is it possible to produce rotation in a single-phase alternating current field?

So far as they have done so is sufficiently indicated by the foregoing statements concerning the apparatus used, its manipulation, and the results obtained.

This experimental work was carried on in connection with an Honorary Fellowship in Electrical Engineering, during the college year of 1901 and 1902, at the University of Wisconsin, under the direction of Professor Dugald C. Jackson.

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